# Designing and Analyzing Residential Passive Cooling and Energy Efficiency Strategies in Hawai‘i

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December 2011

*Submitted towards the fulfillment of the requirements for the Doctor of Architecture Degree.*

School of Architecture
University of Hawai‘i

**Doctorate Project Committee**
Stephen Meder, Chairperson
Eileen Peppard
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*We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in fulfillment as a Doctorate Project for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Mānoa.*

Doctorate Project Committee

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# *CHAPTER 1 PROJECT BACKGROUND*

## ***1.1 ABSTRACT***

This project is designed to help develop a more climate appropriate residential architecture in the State of Hawai‘i. There is an opportunity and need to improve home design in Hawai‘i in order to maximize day lighting, provide natural thermal comfort all year, take advantage of the trade winds to cool the interior, keep the occupants comfortable without using mechanical systems such as air conditioning, and through all of these strategies, conserve electricity. The goals for this project are to research and design for the topics of passive solar cooling design, day lighting, thermal comfort and natural ventilation; and specifically how to use these strategies in the predominately cooling climate of Hawai‘i. The researched design strategies will be applied, then tested for effectiveness in the Hawaiian climate and, specifically, on the site chosen for the project. The design will then be analyzed and further modified to achieve the greatest potential energy efficient and naturally comfortable design. This project will become a useful published source as a case study for new or retrofitted projects in Hawai‘i.

The project is aimed to provide homes for Hawai‘i that are affordable, attractive, comfortable, functional, healthy and environmentally friendly. The homes designed for this project will be at least 30% more energy efficient than required by Hawai‘i state energy codes, and provide at least 30% more natural light access than city code demands. These homes will bring a new standard of comfort and efficiency to Hawaiian homes.

The first phase of this project is the research phase. The topics studied for this project include passive cooling techniques, daylighting, thermal comfort, natural ventilation, the macro and micro climatic data for Hawai‘i and effective building materials to help mitigate interior heat. This project will use what is learned from the research phase and apply it successfully into a new residential design strategy in Hawai‘i.

The second phase of the project is the design phase. Computer models will be created for simulation and verification using the computer program Ecotect to test the designs. This will provide the most useful quantifiable data on the design’s effectiveness. The understanding about how different components are affected, either positively or negatively, will be shown through testing and re-testing many different design possibilities.

## *1.2 INTRODUCTION*

The plan for this D. Arch thesis project is to design and analyze two prototypical passive solar and energy efficient single family residences specific to the Hawaiian climate (hot-humid) that can be used as a guideline for future students and architects. Sustainable, environmentally friendly and "green" architecture have been around for thousands of years and have only recently been getting more exposure and development. The necessity to design homes that have more daylight, are naturally thermally comfortable without the need for air conditioning, and bring in natural air flow is not just a trend anymore. Green design has become necessary to help stop our negative impact on the earth and the depletion of its natural resources. This project will focus research on the topics of passive solar cooling, daylighting, thermal comfort and natural ventilation. This project aims to continue the research and development of these topics. After researching the topics, 21 single family homes comprised of two plan types will be designed for a development in Hawai‘i which incorporates all of these passive design features and greatly reduces the energy use and lifetime costs of the houses.
Computer modeling programs such as Ecotect and WinAir will be used in the early stages of design to test design features such as window size and placement, room size in relation to wall height and depth of the room, building size and shape, roof type and overhang length, and the materials used. These programs will show the effect of the design relating to solar gains and losses throughout the year, interior and exterior temperatures compared to the natural comfort zone, day lighting levels in each naturally lit space, and airflow rates and directions. Knowledge of this program will help to test, document and record data on the effectiveness of the design of the houses for Hawai‘i. Using Ecotect is a useful way to gain specific quantifiable data for a project while it is still in the design phase, when it is most critical to test and modify the design. The recorded data will be added to the document to show the positive results of what has been designed versus a base case model. The final design will be compared to a base case house in Hawai‘i that meets the minimum energy efficiency standards stated in the Hawaii Model Energy Code.

The Leadership in Energy and Environmental Design (LEED) certification process and credits will provide a useful template and metric to evaluate the performance of the buildings. Using LEED credits as a metric for the components, materials, and construction techniques is a way to follow certain building requirements by a nationally recognized organization which aims at improving the performance of houses; however this project will not necessarily be aiming for building certification. The standards set for receiving LEED points are substantially higher than the minimum energy requirements set in Hawaii, which if achieved will prove that the final design not only meets, but exceeds standards in daylighting levels, energy efficiency, interior thermal comfort and airflow rates in Hawai‘i.

Located in the Lualualei *Ahupua‘a* (the traditional Hawaiian land division system), the Green Homes at Lualualei has goals set to build twenty-one 1,300 square foot single family homes on 2.77 acres in Waianae, on the west coast of Oahu, Hawai‘i. Each home will have approximately 1,300 square feet of living area which will include three bedrooms, two full bathrooms, a two car carport plus parking for two more in the driveway, a solar water heating system, energy efficient appliances and lighting, low flow faucets and toilets, and personal fruit and vegetable gardens. The Green Homes at Lualualei has three objectives: building affordable homes for the residents of Waianae, setting an example of green development and living in order to inspire future developments and providing a healthy living environment. The hope is that this project will set an example of green development and living in order to inspire future developments of sustainable, green housing in Hawai‘i.

To show that the final design and results are effective, the houses in the development will be analyzed using computer simulation software. The software will quantify the results and show the effectiveness of the design based on a comparison to a base model design that meets energy codes such as the Hawaii Model Energy Code. Through the testing, the houses will aim to reach standards set by the USGBC’s LEED for Homes. The first part of this project will consist of researching and documenting the strategies used in the areas of passive solar cooling, day lighting, thermal comfort and natural ventilation. The second part will apply knowledge from the research to the design of single family residential houses for Hawai‘i which will be naturally comfortable and energy efficient. The third part of the project will analyze the effectiveness of the house designs using the computer model simulation program, Ecotect. The deliverable for this project will be innovative, naturally comfortable and energy efficient houses for the development in Hawaiʻi, on which other projects can be based.

A high-performance home will have design strategies that result in improved resource efficiency, selection of environmentally responsible and high-performance materials, equipment and systems, and construction practices ensuring that each of the measures is installed properly. This project will include day lighting strategies, adequate natural ventilation to cool the interior, solar hot water heating systems, energy efficient appliances, materials that mitigate heat gain and reflect the sun's radiation, the most efficient site and building orientation, community recycling, vermi composting, mulching, barbeque and park area, a native species garden, a playground for neighborhood children, access to public transportation, plenty of privacy, and for some of the lots, ocean views.

The issues of water catchment and photovoltaic panels will also be researched and may be included in the final design, though it will be dependant upon the findings of the research. With the exception of the renewable technologies, all of the features to be included in the homes will improve comfort and energy efficiency through the design and the placement of the buildings on the site. It is possible to reduce the energy demands of a house through specific educated design decisions that will not add to the up front cost of a project. Systems such as photovoltaic panels and solar water heating will cost more up front, but will greatly contribute to the energy savings of the houses.

## *1.3 BACKGROUND/ FIELD OF STUDY*

Buildings use energy every day, all day long. They use energy to keep us warm in the winter and cool in the summer. They use energy to provide us with light whenever we need it. They use energy to provide us with hot water, and they use energy to run all of our appliances, computers, televisions, radios, etc. There are numerous ways for us to save energy in our homes, offices, restaurants, and in any and every building type. As David Miller stated in his book Toward a New Regionalism: Environmental Architecture in the Pacific Northwest, a new definition of sustainability is "Design in which energy use is minimized and renewable resources are maximized; it creates an enduring architecture that works with nature's systems and cycles."

There are many books and articles related to the topics of focus: passive solar cooling, day lighting, thermal comfort and natural ventilation. All of these topics have been thoroughly studied and documented. Most of the resources are general, meaning that they have shown case studies and guidelines for designing in all the climates in the U.S. In fact, the majority of the information in most of these books is about how to heat a building in a temperate climate using passive strategies, not cool them, which is the challenge of this project. A large portion of each book is case studies which show the systems and features of the research utilized in buildings. This project will be different because the research will introduce a new design that will then be tested to show thermal comfort and daylight levels inside the building, translating into energy and monetary savings solely through the building design. Simulation software can help the designer test the building and gain quantifiable information based on weather data for the location. This information is not guaranteed, however, and can only be verified through actual construction and post occupancy testing.

The focus of the research is on designing for a tropical climate, for which an energy efficient and naturally comfortable single family residential house for Hawai‘i will be developed. There are many books that have been written on tropical building design that include segments on designing for the Hawaiian climate. Two books that have been researched and written in Hawai‘i with design guidelines and strategies specifically for the islands are the *Hawaii Home Energy Book* by Jim Pearson and the

*Field Guide for Energy Performance, Comfort, and Value in Hawaii Homes* produced by the State of Hawaii DBEDT and the Honolulu Chapter of the AIA. The Hawaii Home Energy Book (published in 1978) and the Field Guide for Energy Performance, Comfort, and Value in Hawaii Homes (published in 2001) both have strategies and guidelines which are timeless, and like these books, this project aims to continue the investigation into designing and building homes specifically for the climate of Hawaiʻi. These books will serve as the basis for this project. Much of the world has both heating and cooling climates, which means the design needs to be flexible. Passive cooling, day lighting, thermal comfort and natural ventilation are all very closely related and should be designed as an integrated system to create a naturally comfortable and energy efficient single family residential house for the Hawaiian climate.

Although there have been many improvements in green systems, technology and materials, and these systems are becoming cheaper, Hawaiʻi is not seeing an improvement in the way homes are designed and built. There is an opportunity here to provide affordable homes designed to improve energy efficiency and natural comfort without requiring mechanical air conditioning.

# *CHAPTER 2 GENERAL CLIMATE DATA FOR HAWAI‘I*

## ***2.1   HAWAI‘I CLIMATIC DATA***

Hawai‘i has one of the mildest, most pleasant climates in the world. The climate is warm, humid and very consistent, with only moderate changes in temperature throughout the year. For the majority of the year in Hawai‘i building occupants can feel comfortable without the assistance of air conditioners or room fans which use a lot of energy and cost the building owner money. This project will show how a home can be designed to be naturally ventilated and remain comfortable throughout the year without the need for air conditioning. There are too many Hawaiian homes that do not take advantage of passive solar design, but instead designers and builders have ignored the climate and designed homes to be mechanically conditioned at a high cost to the occupants and the planet.

There are two seasons in Hawai‘i: the summer months, *kau* in Hawaiian, which occur from May to October, and the winter months, *ho‘oilo*, which occur from November to April. In Honolulu, on average, the hottest month of the year is August with temperatures ranging from 74° F to 88° F, and an average temperature of 81° F. The coolest month of the year is January with temperatures ranging from 66° F to 80° F, and an average of 73° F (Climate Zone). For the entire state of Hawai‘i the yearly average temperature is about 80° F (*see Fig. 2.1.1*).

The overall average humidity levels in Hawai‘i are below the US average for the afternoon and evening hours, and on average for morning hours (*see Fig. 2.1.2*). Humidity levels change from month to month as well as the time of the day. In Honolulu, the yearly average relative humidity levels range from 67% to 81% in the morning, and 52% to 62% in the afternoon, with higher humidity percentages in the winter months, and lower percentages during the summer (City Data). However, the relative humidity is more of a comfort problem in the summer months due to increased temperatures.

There is a great diversity in climatic conditions found in Hawai‘i and the differences in temperature depend on what island, and what part of the island, the reading is taken. The endless variety of mountain peaks, valleys, ridges, and broad slopes on the islands create a climate that is different from the surrounding Pacific Ocean, as well as differences in climate within the islands. The mountains obstruct, deflect and accelerate the flow of air. When it is warm, the moist air will rise over windward coasts and slopes, creating clouds and rainfall. In the leeward areas, where the air descends, the weather tends to be dry and sunny. The elevations in Hawaiʻi range from sea level to nearly 14,000 feet above sea level at Mauna Kea on the Big Island of Hawaii. The air temperature will generally cool about 3.5° F per 1,000 feet of elevation gain. The lowest temperature ever recorded in Hawaiʻi was on the top of Mount Haleakala on Maui in January of 1961, when it was 11° F. The hottest temperature was in the Puna District on the Big Island in 1931, when the temperature was a scorching (for Hawaiʻi) 100° F (Netstate). "The cooling effect of trade winds, low humidity, high pressure, clear sunny days, negative ionization from the sea, and an almost complete lack of industrial pollution combine to make Hawaii not only the most healthful spot in America but one of the most comfortable places on Earth" (Salmon).

The great diversity in climate and the geography of the islands creates a large diversity in precipitation across the islands. The climate of the islands ranges from dry, arid desert to the wettest place on Earth at Mount Waialeale on Kauai, which averages 460 inches of rainfall annually (Netstate). Honolulu has a moderate amount of rainfall for the island of Oahu (*see Fig. 2.1.3*). Honolulu is above average for the amount of precipitation compared to the US average for the months of October through April. From May through September, Honolulu is on the high side of the US average (City Data).

The winter sun at noon on December 21 will be at an extreme low angle of 45° above the southern horizon, while at noon on June 21 in the summer it will move to an angle of 93° above the southern horizon, meaning it will be at 3° above the northern horizon. It is unique to Hawaii of all the 50 states that the summer sun shines from the north; this is due to its being south of the Tropic of Cancer. Geographically, Hawaiʻi has the most southern point in the nation, and being so close to the equator, the length of days change only a little over two and a half hours throughout the year. The shortest day of the year is on the winter solstice, December 21. The sun will rise at 7:04 am and will set at 5:55 pm, which is 10 hours, 50 minutes and 10 seconds day length. The longest day of the year is on the summer solstice, June 21. The sun rises at 5:50 am and sets at 7:16 pm, resulting in 13 hours, 25 minutes and 56 seconds day length (Time and Date). The closely uniform day lengths result in small seasonal variations in solar radiation and therefore temperature difference. Many houses in the mainland United States have to be designed to protect from the sun's heat during the summer and take advantage of its heat in the winter while trying to bring in natural light throughout the whole year. In most locations in Hawai'i it is necessary to mitigate the heat gain from the interior of the home, and to allow for both natural ventilation and daylight for the whole year.

Hawaii's a warm and humid climate, so buildings need to be designed to mitigate heat gain into the interior year round. This is accomplished by minimizing direct sunlight from the interior (through a variety of strategies discussed later), and keeping an adequate level of air movement through each home, which can alleviate the need for expensive and often unneccesary mechanical conditioning. As the prices of energy increase every year, so will the electric bills to users of poorly designed, mechanically conditioned houses.

During the summer, trade winds prevail more than 90% of the time. The winds blow at an average of 15-20 mph during the summer, and can reach speeds much higher throughout the year (*see Fig. 2.1.4*). With the winds blowing steadily and at a relatively gentle rate, it is advantageous to capture the breezes and direct the flow through the building. During the winter months, trade winds prevail only about 40-60% of the time, and decrease in velocity to an average of about 10 mph (Pacific Disaster Center). Periodically during the year, the winds switch directions in Hawai'i and blow out of the south to southwest; these are known as *kona* winds. Kona winds are most common during the winter months, but happen periodically throughout the year, and they most often bring high humidity and rain.

A bioclimatic chart will show the range of temperatures and relative humidity for a specific location used for passive solar design. By using the average high and low monthly temperatures and relative humidity percentages we can see what methods of cooling or heating are required for the specific climate. The bioclimatic chart shows the natural comfort zone and design strategy zones including natural ventilation, high thermal mass, evaporative cooling, high thermal mass with night ventilation and passive solar heating. We can see the monthly range of temperature and relative humidity by plotting two points on the bioclimatic chart and connecting them with a line. The first point is plotted at the average monthly high relative humidity percentage and the average monthly low temperature, and then plotting a point at the average monthly low relative humidity percentage and the average monthly high temperature. This line represents the changes in temperature and relative humidity for the given month. When plotting all months on the bioclimatic chart we can see what type or types of passive solar design will be required based on the climate conditions. For this project and site the bioclimatic chart shows that Waianae is within the natural comfort band about half the year and interior comfort can be achieved through natural ventilation for the majority of times outside the comfort zone. There are a few days throughout the year that would require passive solar heating based on the bioclimatic chart recommendations, but for this specific location passive solar heating will not be necessary (*see Fig. 2.1.5*).

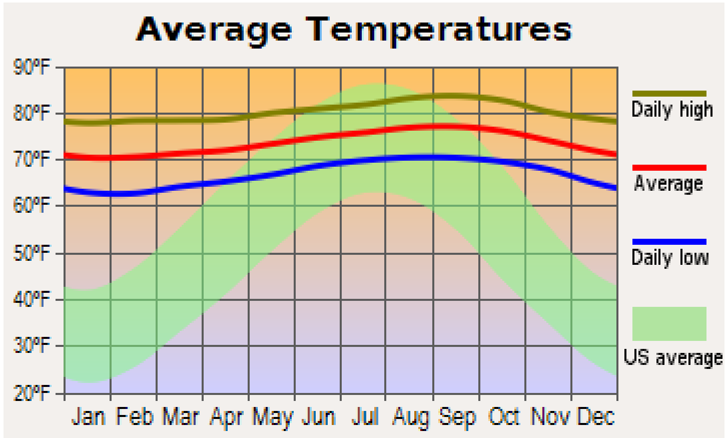



Fig. 2.1.1 Average annual temperatures for Honolulu
*Source: www.city-data.com*

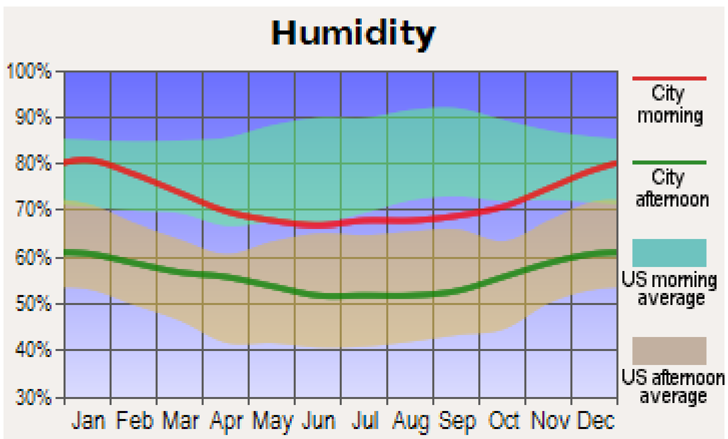



Fig. 2.1.2 Average humidity for Honolulu
*Source: www.city-data.com*

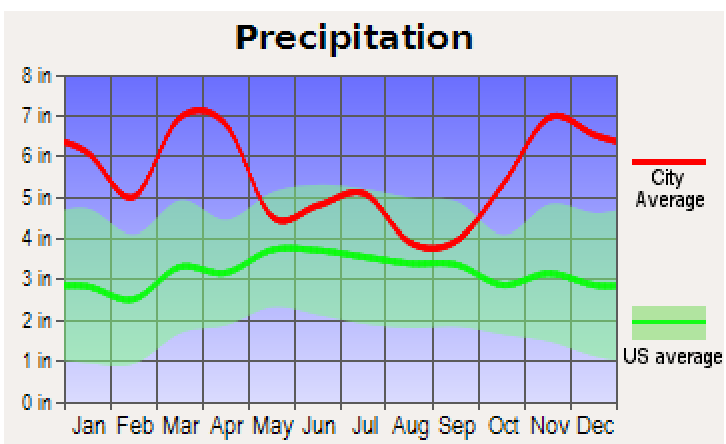



Fig. 2.1.3 Average precipitation for Honolulu
*Source: www.city-data.com*

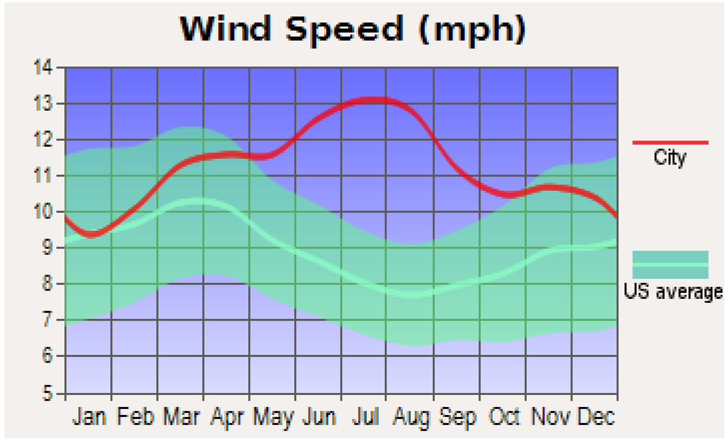



Fig. 2.1.4  Average wind speed for Honolulu
*Source: www.city-data.com*

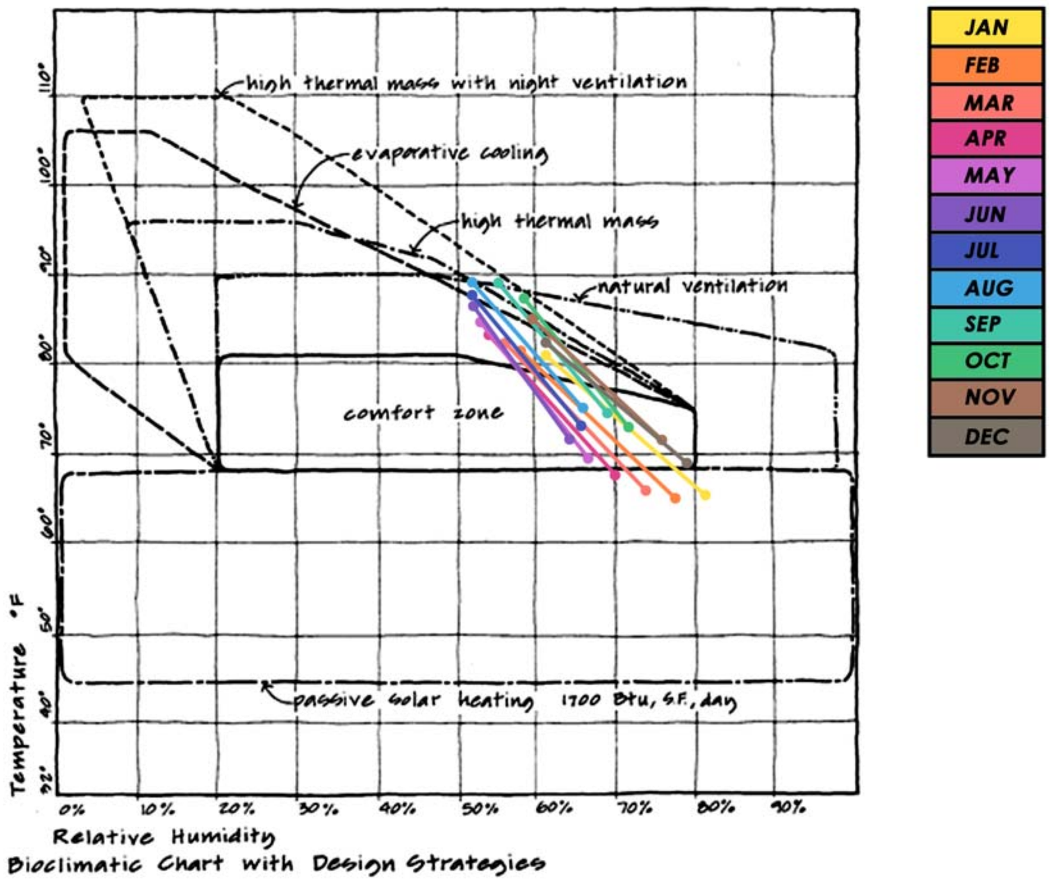



Fig. 2.1.5 Bioclimatic chart with design strategies and the monthly average temperatures and humidity for Waianae plotted over the graph

## ***3.1 SITE AND MICROCLIMATIC DATA***

Green Homes at Lualualei
TMK 1-8-7-033: 011 & 022
87-1720 Farrington Highway
Waianae, HI 96793

Waianae, Oahu , Hawai‘i - 21° 49' Latitude 158° 24' Longitude

The project site plan and the individual home designs will work together synergistically to create a green living space. The site for the Green Homes at Lualualei development is in the Waianae area on the west coast of Oahu (*see Figs. 3.1.1 – 3.1.6*). The project site is conveniently located along Farrington Highway, providing easy access to shops, restaurants, public parks and public transportation. Currently, The Bus has a stop at the front (west) side of the property along Farrington Highway. The entrance to the project development will be designed to include turn-in and turn-out lanes and a pull off area for a bus to fully exit Farrington Highway to provide a safer area for riders, pedestrians and drivers. All necessary public utilities already exist at the project site, minimizing the need for additional infrastructure.

The site has a total land area of 2.77 acres, or 120,684 square feet. There is an average elevation of 10 feet above sea level across the site, with a minimal slope of about 1.5 percent from the south to the north corners. The ocean side of the lot is about 75 yards from the water's edge, and sited right along Farrington Highway. The slope of the site starts at about 10' above sea level on the south corner, then dips to about 7' above sea level in the middle of the site, then rises to about 15' at the north corner. The site is split almost perfectly in half by a drainage channel that connects the valley's waterways with the ocean. There is a pre-existing bridge that spans the drainage channel connecting the two parcels on the east side of the site. The drainage channel is considered state land, and cannot be developed beyond some minor landscaping. The state requires access to the channel for maintenance and scheduled cleanings. There is an existing 6' high chain link fence around the drainage channel on all four sides. The mountain (*mauka*) portion of the site has a total useable area of 65,860 square feet. The ocean (*makai*) portion of the site is 54,824 square feet in area. The mauka parcel will be used solely for 13 homes, while the makai parcel will house eight homes and have two park and garden areas on the ocean side to act as a buffer from the busy highway and a pleasant gathering area for the neighborhood.

This site is located in a residential area with many amenities in close proximity. Farrington Highway is directly to the south-west of the site, and residential neighborhoods on the remaining three sides. The site has existing 6' high chain link fences along all sides that are adjacent to other residential homes. Along the lower makai parcel on the west side is a small road and there is no fence along this portion. There are no structures that could intrude on the solar access of the homes on the site. To the north-west of the site along Farrington Highway is a mountain peak at Maili Point, which will help shade the site from late afternoon sun throughout the year. Other than the peak at Maili Point and the Kiawe trees on the site, there will be total access to the winds and the sun.

Currently the site has no built structures on the land (*see Figs. 3.1.7 – 3.1.12*). The site is covered in Kiawe trees, 3' tall wild grass, small shrubs, wild aloe and some wild cherry tomatoes. The layer of soil is less than one foot in depth and resides on a dense coral limestone ledge. The soil layer is too thin for agricultural purposes and has limited the growth of plants in some areas. There are some places on the site where there is no soil layer at all and the coral is exposed. This condition may prove to be a difficulty in constructing the foundation for the homes. The majority of the site and the shading it provides are from the many Kiawe trees covering the site. The trees grow to about 30' tall and will provide great sun protection for the homes. The site has been surveyed and many of the trees have been marked as part of the final landscaping of the development. It is far better to work with the existing trees that are proven to live and thrive on the site than to bring in new landscaping that might not thrive in this microclimate.

Waianae is located on the hotter, drier side of the island of Oahu. Typically Waianae is a few degrees hotter, has more sunny days, gets much less rainfall and receives less wind than the rest of Oahu. The yearly average for Waianae is 272 sunny days, while the US average is only 202 days. The average temperature ranges from 71°F in the winter to 80°F in the summer. The average minimum and average maximum temperatures range from 63°F in the winter to 88°F in the summer. This shows a yearly average temperature of 79.5°F (*see Figs. 3.1.13 and 3.1.14*). The average annual rainfall in Waianae is 20.93 inches, and unfortunately, it is not enough rainfall to be able to capture it for effective reuse in homes in Waianae. January receives the most rain with an average monthly rainfall of 3.54 inches, and August receives the least with an average of 0.56 inches (City Data). There is a possibility enough water could be captured to be able to water the landscaping of the development, but that will depend on the cost offset of installing a water catchment system. This will be discussed more in depth later.

With the site being in such a hot and humid climate, the homes will need to take full advantage of the winds to help cool the interior to keep the homes naturally comfortable. The west side of Oahu has the least amount of wind due to the topography of the island and the direction of the winds. To the north and east of Waianae is the island's tallest mountain peak, Mt. Ka'ala with an elevation of 4,025 feet. Due to the height and the close proximity of the mountain to the site much of the trade winds are blocked or slowed. However there are some prevailing sea breezes which blow into the site from the south and west throughout the year. Typically winds do not reach over 15 mph in Waianae, however there are times with higher wind gusts, and times with no wind at all. On average the wind will blow from the east-northeast at about 5-15 mph.

This site was chosen for the ability to capture the trade winds and daylight. The property currently has very few plants, but many trees, which gives the opportunity to landscape it to properly shade the site and the buildings. There are no obstructions on the south side of the property which would inhibit the amount of daylight or prevailing winds. The trade winds usually blow from the northeast and east-northeast direction most of the year, and are strongest during the summer months and lightest in the winter.

The local microclimatic data necessary to analyze and design for are the temperature extremes, relative humidity, solar radiation, and the trade and kona wind effects throughout the year. The data should be adapted to the living level to provide natural comfort year round. It is best to first look at the macroclimate of the state of Hawai'i, then the town of Waianae, then at the extreme microclimatic scale of the site itself.

Fig. 3.1.1  Digital map of the island of Oahu
*Source: Google Earth*

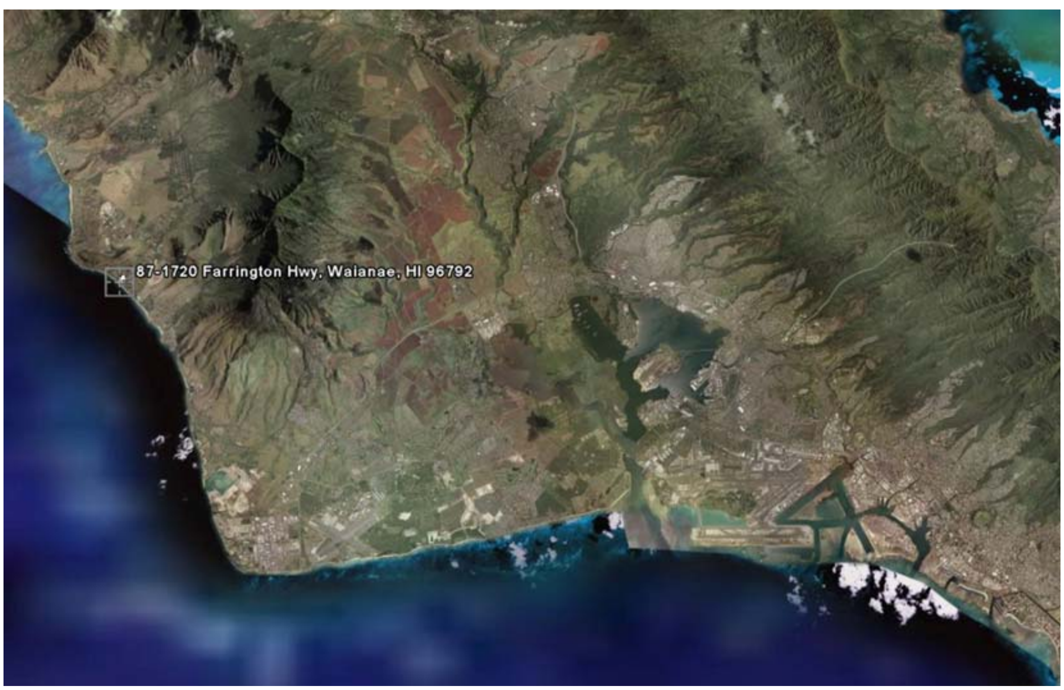


Fig. 3.1.2  Digital map showing south-west Oahu
*Source: Google Earth*


Fig. 3.1.3  Digital map of the area of Lualualei, the site is outlined in white
*Source: Google Earth*

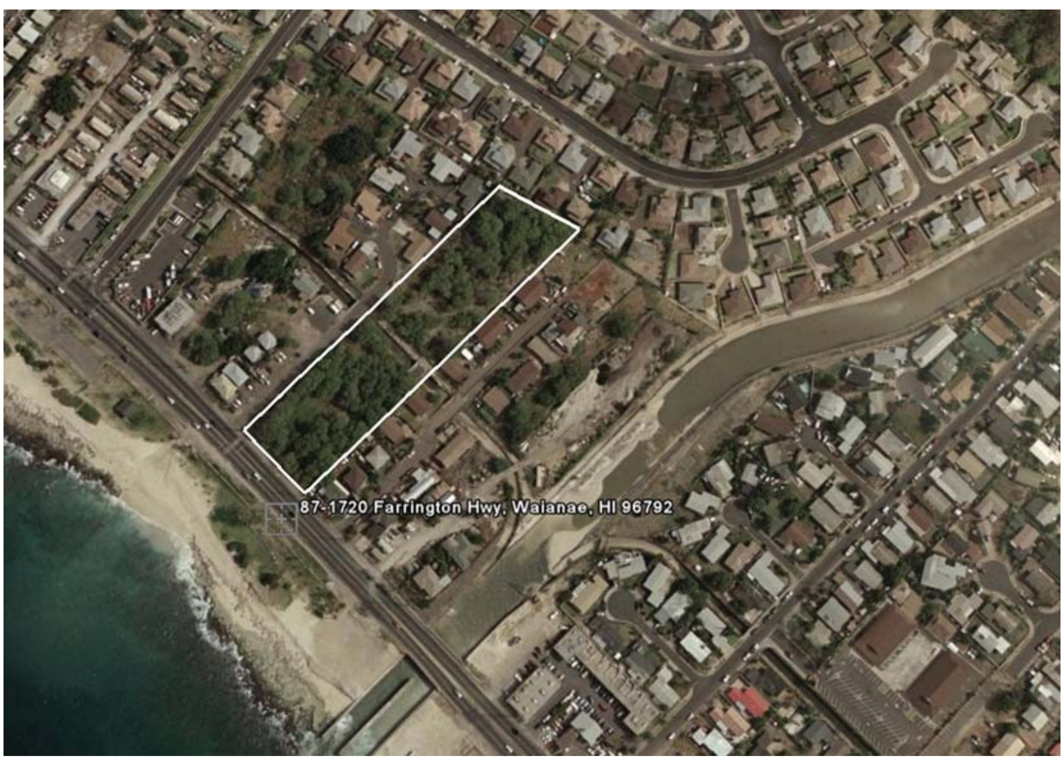



Fig. 3.1.4  Digital map showing the surrounding neighborhood around the site (outlined in white)
*Source: Google Earth*


Fig. 3.1.5  View looking north of a digital aerial map showing the topography of surrounding area
*Source: Google Earth*


Fig. 3.1.6  View looking south of a digital aerial map showing the topography of surrounding area
*Source: Google Earth*


Fig. 3.1.7 View of site from the beach showing surrounding area and mountains

Fig. 3.1.8 View of undeveloped site from across Farrington Highway

Fig. 3.1.9 View of the front of the site showing the proximity to Farrington Highway

Fig. 3.1.10 View of the current condition of the site which has natural vegetation and no structures

Fig. 3.1.11 View of the Ulehawa drainage channel which separates the two parcels

Fig. 3.1.12 View looking towards the ocean of the existing bridge which connects the two parcels

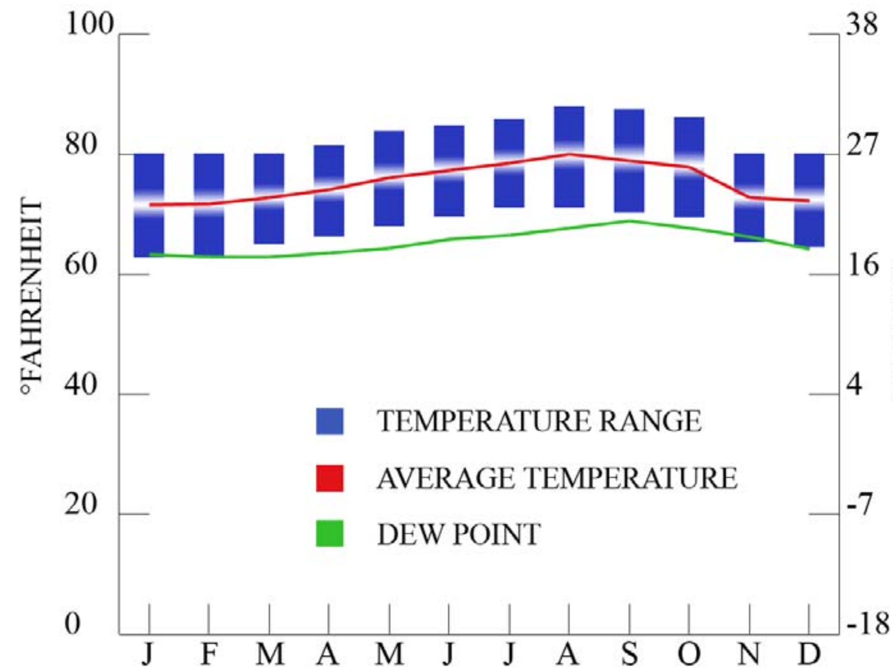



Fig. 3.1.13 Chart showing the temperature range and dew point for Lualualei

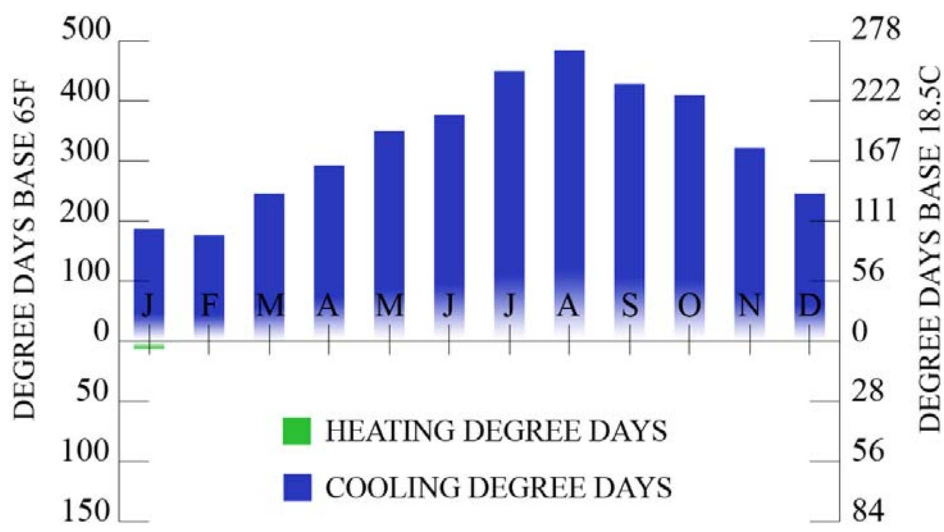



Fig. 3.1.14 Chart showing the cooling and heating degree days for Lualualei

## ***3.2 ZONING INFORMATION***

*Honolulu LUO Sec. 21-2.110-1 – Cluster Housing Permit*

Before the submission of a cluster housing, agricultural or country cluster application, the applicant may undergo a 21-day conceptual review of the project by submitting a preliminary site plan drawn to scale showing the approximate location and dimensions of all proposed structures, roadways, common open areas and recreational facilities. Included on the preliminary site plan shall be a conceptual landscaping plan, with existing contours at vertical intervals of five feet where the slope is greater than 10 percent and not more than two feet where the slope is less than 10 percent. Any areas designated for grading shall be indicated and approximate amounts of cut or fill shown.

The site plan showing the location of houses, parks, roads and sidewalks has been designed. There will also be a landscaping plan, which will show typical house lot landscaping and the landscaping of the entrance, park area and native species garden. Each tenant will have the choice to landscape the lot as they see fit, but a general landscaping plan will be produced as an example for the lots to take into consideration.

The land is zoned R5 residential district, is in a Federal FIRM flood zone, and is part of the state special management area. The flood zone height restrictions cover 61% of the ocean portion of the site. Of the 61% of flood restriction area, 37% has a height restriction for living areas to be a minimum of 12’ above sea level, and the other 63% has a living area height restriction of 10’ above sea level (Honolulu Land Information). The elevations of the land at the flood zones range from about 5’ to about 7’. The minimum height that a living area can be in this zone is about 7’ above grade. All the houses built in the flood zones will have the living area built at 11’ above grade. The rest of the ocean portion of the lot and the entire mauka portion allows for the houses to be built on grade. There is also a small area in the ocean portion that is restricted of building any structures whatsoever, but this area will contain part of the park area which has no structures (*see Figs. 3.2.1 and 3.2.2*).


Fig. 3.2.1 Map showing the Flood Zone height requirements, and Flood Zones for the site. The orange band designates the VE zone which has the most building regulations; the site has only a small portion which will not be built upon. The purple band is the AE zone which regulates building living area below the minimum height shown on the map. The height regulations for the bottom parcel are designated by the red band which has a minimum living area height of 12' above sea level, and the yellow band which regulates living area to 10' above sea level. *Source: gis.hicentral.com*


Fig. 3.2.2 Map showing the Zoning Designations. The site (outlined in red) is zoned as R-5 residential. The red boxes show Business zoning districts and the green band (beach) is zoned as a preservation district. *Source: gis.hicentral.com*

*Honolulu LUO  Sec. 21-2.110-1 – Cluster Housing Requirements*

This project will be designed as a Cluster Housing development, giving more flexibility to lot size and setbacks, and allowing for more homes to be built on the lot. The requirements for cluster housing aim to maximize open space, preserve natural features and major landscaping, provide a variety of views and visual interests, create landscapes that are interesting and provide privacy, and create lots with a sense of individuality.  The guidelines recommend a variety in building setback and siting, especially where repetitious plans and models are to be used for economy.  This project will include two model types and take into account the recommendations for the design of the site.

The first step taken in site analysis is to look at the street layout options.  Nine different street layouts have been drawn showing the street on the west, middle and east side of each parcel.  With each variation in street layout, the useable square footage is calculated and range from a low of 89,538 sq. ft. to a high of 97,415 sq. ft (*see Figs. 3.2.3 – 3.2.6*).  Each street layout option presents a different lot division and maximum number of houses which can be built.  Once the final site layout has been selected, the next step is to look at building placement, orientation and the maximum number of houses per zoning requirements.  *Figure 3.2.7* shows three versions of the site plan with 32' by 40' houses oriented no more than 15 degrees from due east-west.  The final site layout houses 21 homes oriented 15 degrees south of east.

As per the requirements, the maximum building area is 50% of the zoning lot. The total area of the lot, including both parcels, is 120,684 square feet.  After calculation the maximum building area must not exceed 60,382 square feet.  The maximum number of buildings on the site is calculated by dividing the total lot area by the smallest lot size requirement of 3,750 square feet, which when calculated is 32 homes.  This development is designed to build 21 homes, which is well under the maximum.  The smallest lot size of the development is 4,092 square feet, which meets the minimum requirement of 3,750 square feet.  The maximum height to the top of the roof is 25' above grade, or 30' if the roof incorporates energy efficient features.  Two off-street parking spaces are required per unit, and 50% of the parking spaces can be designed as compact spaces.  It is not required that the parking spaces be covered, however each unit will have a two car covered carport and room for at least two more cars in the driveway.

Cluster housing minimum lot and yard dimensions shall be set by duplex unit regulations. There is a minimum of 10’ front yard setback from the property line to the closest point of a home. Side and rear yard requirements need not be provided in the duplex regulations, however this project will provide more privacy and space by providing a minimum of 5’ for all side and rear setbacks. The minimum dimension between homes is required to be double the side yard requirement of 5’, which makes the minimum 10’. The minimum distance between homes in the development will be no less than 15’, and will be over 20’ for a number of homes.

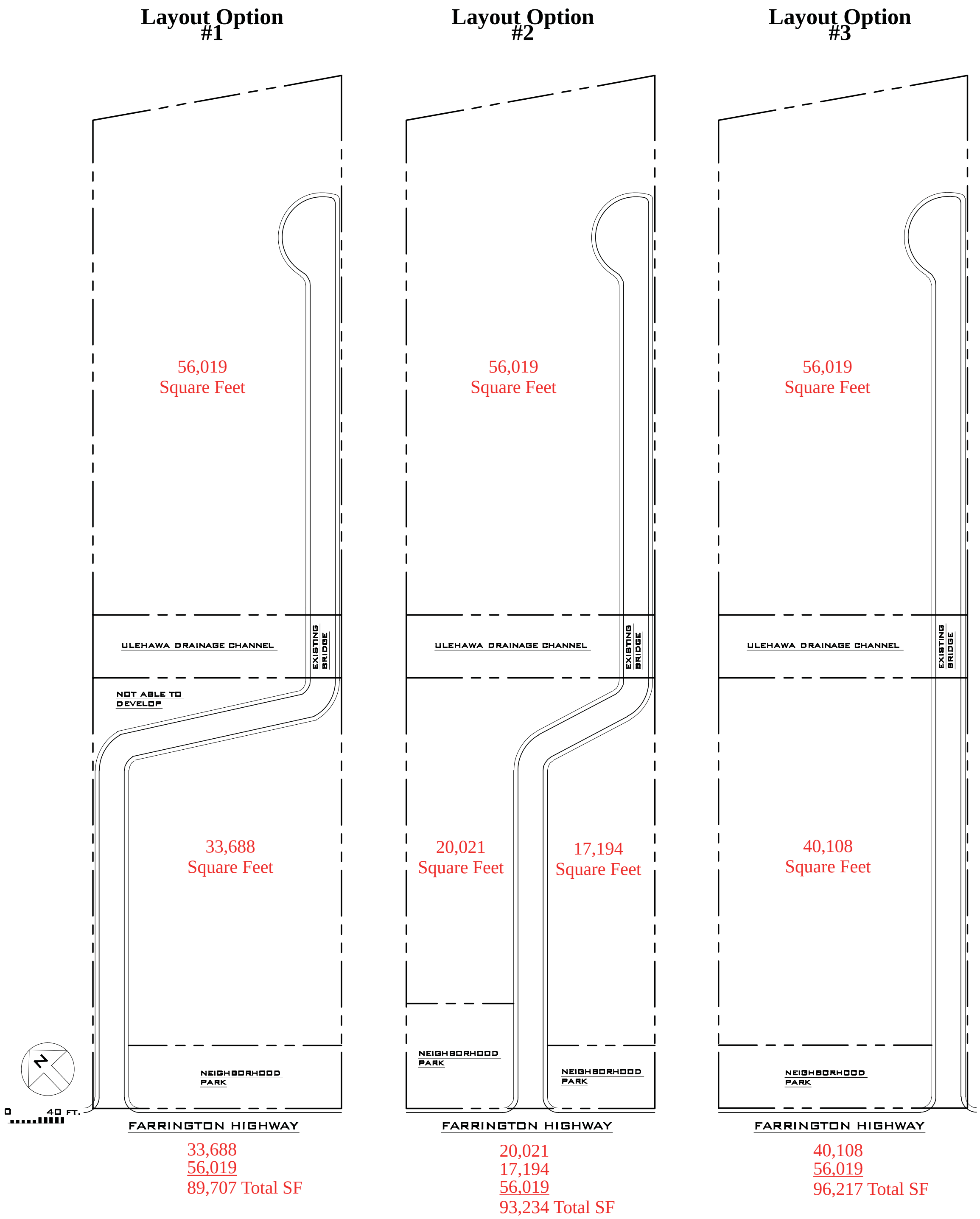



Fig. 3.2.3 - Drawing showing street layout options for the site. Each layout provides different square footages of developable land. The goal is to find the balance of substantial developable area and the optimal layout to maximize building number and correct orientation.

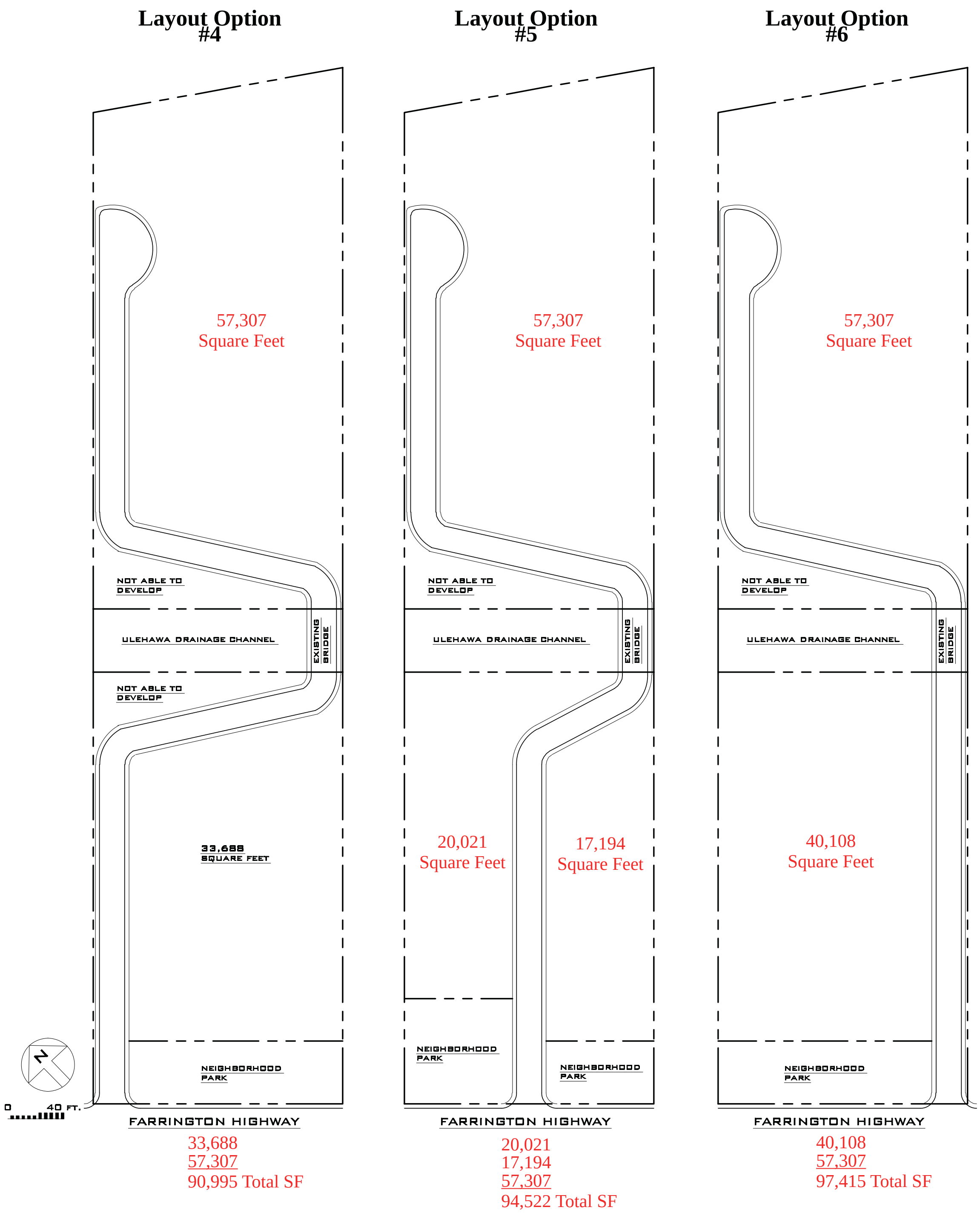



Fig. 3.2.4 - Drawing showing street layout options for the site.

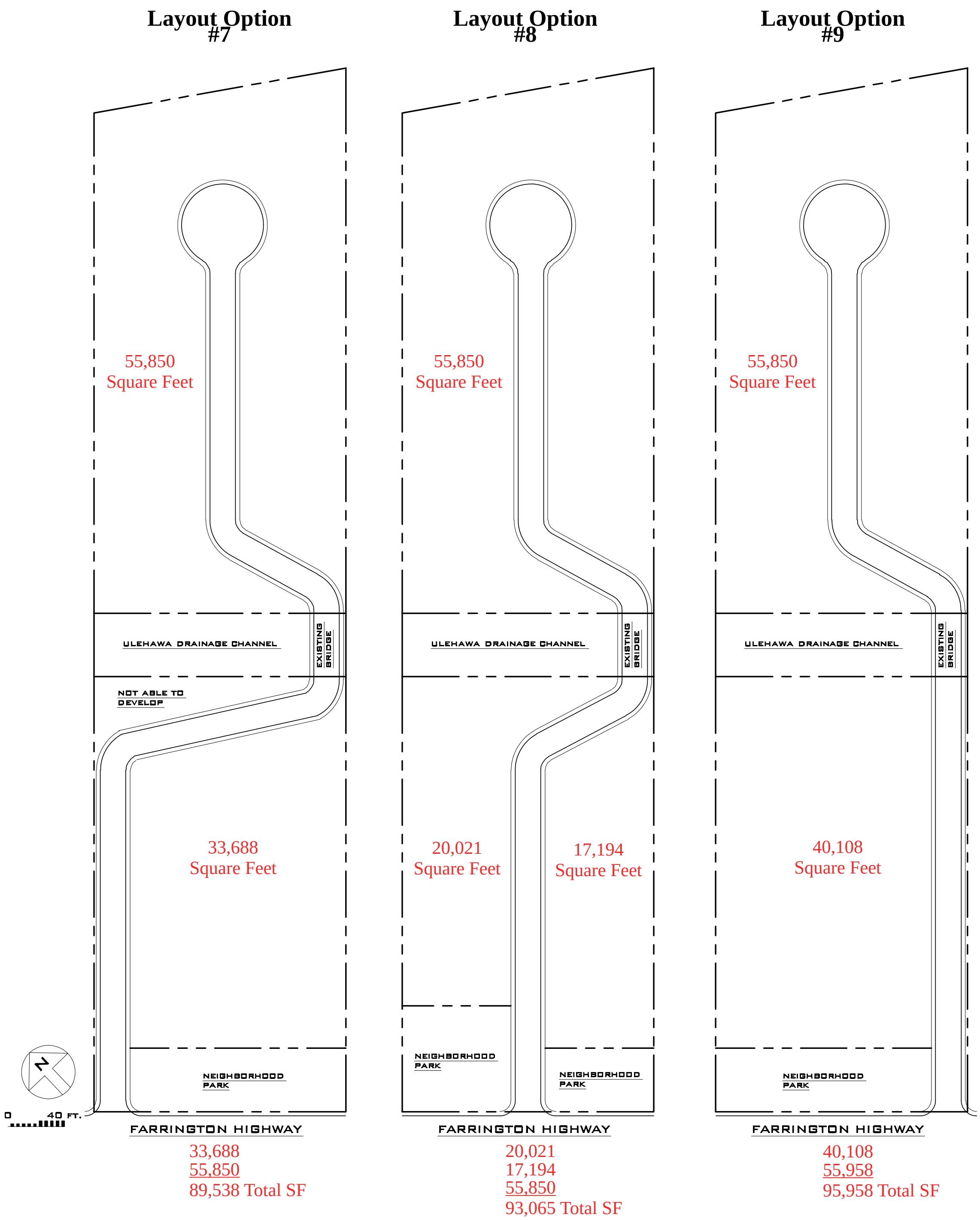



Fig. 3.2.5 - The 9 street layout options range in usable square footage from a low of 89,538 sf (Option #7) to a high of 97,415 sf (Option #6). The site layout chosen for the final has a usable square footage of 93,415 sf (Option #8). This layout will provide lots for homes on each side of the street with the street going through the middle of the site.

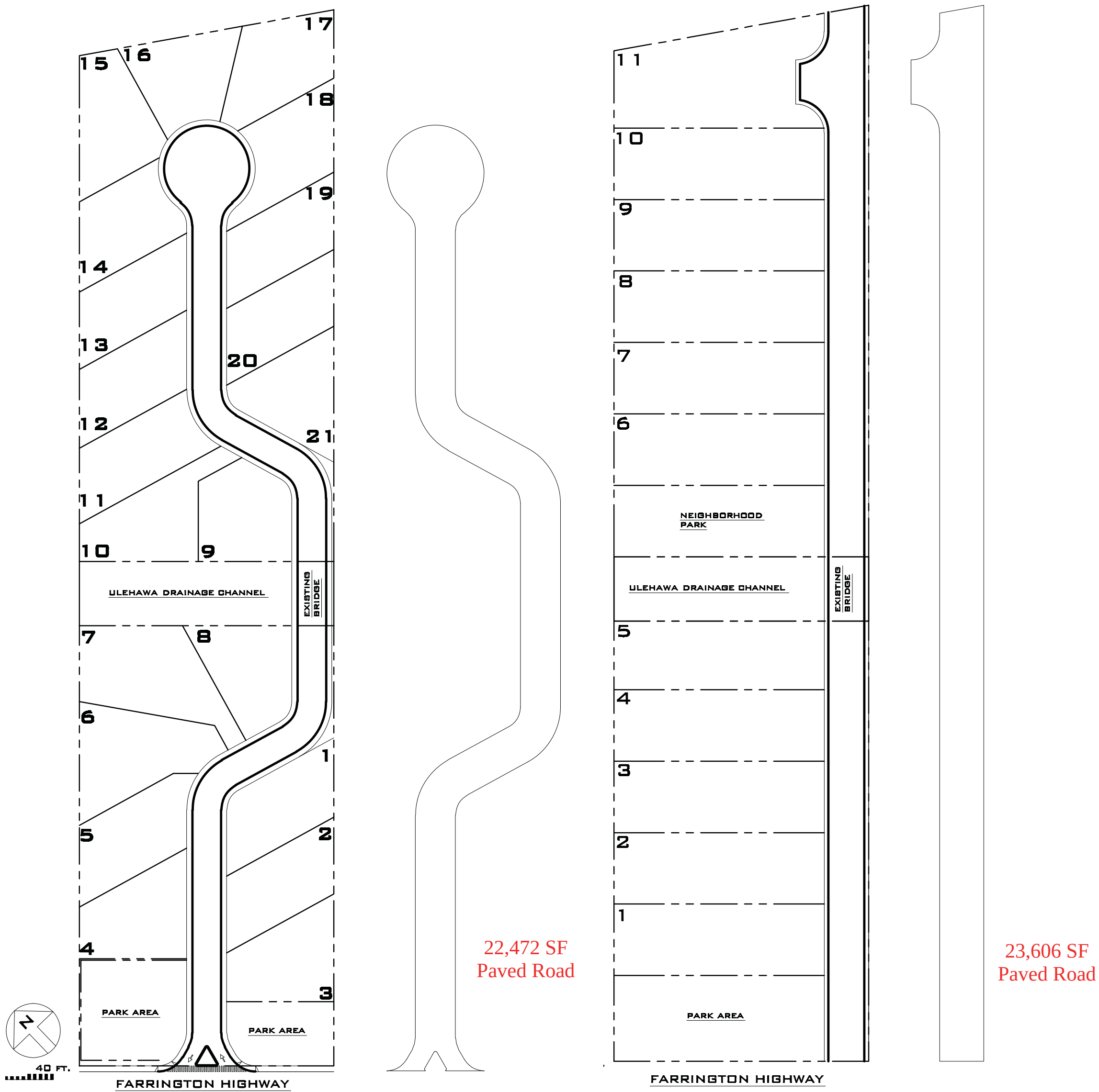
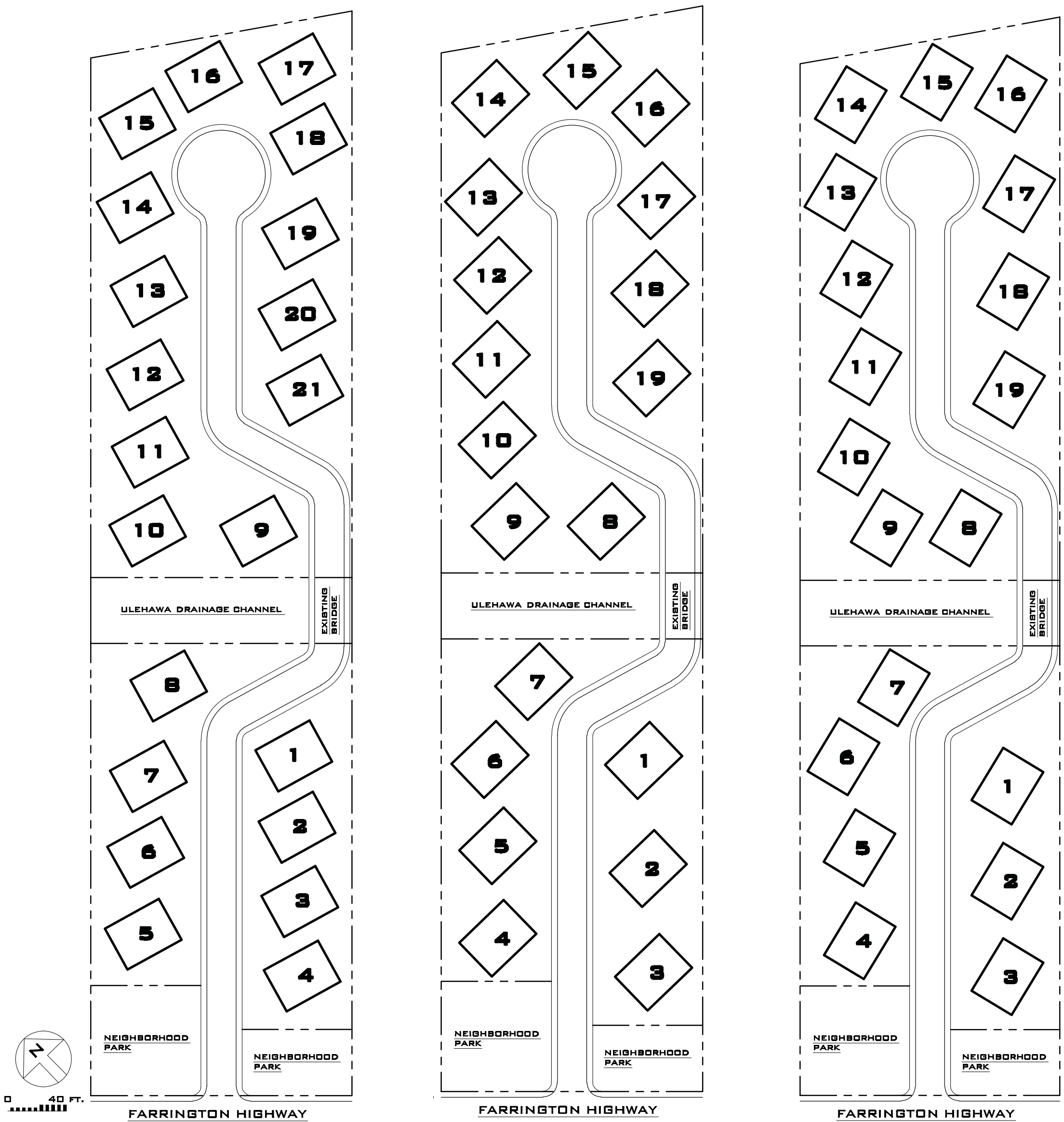



Fig. 3.2.6 - Drawing showing the difference in lot layout with the street pulled to the east side of the site versus the street running through the middle of the site. The advantages to having the street run through the middle of the site are freedom to lay out the individual lots for proper building orientation, and nearly twice as many houses can be built on the site.




15 degrees S of E          True East-West          15 degrees N of E

Fig. 3.2.7 - 32’ x 40’ house “boxes” layed out on the site plan to show various layout options. Sticking to the orientation requirement of no more than 15 degrees of true east-west, the site can fit up to 21 single family homes while also meeting the building setback requirements with a building orientation of 15 degrees south of east.

### ***3.3 BUILDING PROGRAM***

The Green Homes at Lualualei consists of twenty-one 1,300 square foot single family homes on 2.77 acres in Waianae on the west coast of Oahu, Hawai'i. There are two home plans for the project, although only plan one will be used for the final design and analysis. Each home will have approximately 1,300 square feet, and will include an open living area and kitchen, three bedrooms, two full bathrooms, a two car carport plus parking for two more in the driveway, a solar water heating system, energy efficient appliances, low flush toilets, and personal fruit and vegetable gardens. Green Homes at Lualualei has three objectives: building affordable homes for the residents of Waianae, setting an example of green development and living in order to inspire future developments and providing a healthy living environment. In addition to the 21 homes, the development will include two park areas with picnic tables and grilles, community recycling bins and a compost area. The square footage breakdown for each plan is shown below.

Plan Type 1

92 sq. ft. Ground Floor
1186 sq. ft. Second Floor
**1278 sq. ft. Total Living Area**
441 sq. ft. Garage
258 sq. ft. Porch/Lanai

Plan Type 2

759 sq. ft. Ground Floor
742 sq. ft. Second Floor
**1501 sq. ft. Total Living Area**
396 sq. ft. Garage
359 sq. ft. Porch/Lanai

## *3.4 BUILDING DESIGN*

The design features in this project include: the site, the shell, window and door openings, interior elements, water heating and conservation, electric lighting and appliances. More specific details of each of these are listed below. The features suggested here have been derived from the Hawaii BuiltGreen Home Builder guidelines and the LEED for Homes guidelines. A majority of the features listed below will also qualify for LEED for Homes credits.

Site

-Space and arrange homes on site so that all structures have good air flow.
-East-west axis of the building is within 15 degrees of due east-west.
-Homes oriented to maximize cooling potential of prevailing winds.
-Porous paving materials installed to reduce thermal mass, heat gain, and glare.
-Longer sides of homes oriented to face north and south to reduce heat build-up.
-Existing and new landscape elements, trellises, overhangs, and carports to shade homes and paved areas.
-Minimize impervious surfaces on the site to help reduce heat build-up, no more than 10% of site excluding house and carport.

Interior Elements

-Open floor plan designed to provide effective cross ventilation and air flow at body level.
-Floor plan designed to allow all spaces to access natural daylight.
-Interior surfaces use light colors to enhance daylight, but avoid glare.
-Install ceiling fans in living rooms and all bedrooms.
-Homes designed to be air-conditioning free.

Shell

-Light colored resource efficient metal roofing, to meet cool roof standards.

-Use of resource efficient, light colored wall siding (Hardie Siding).

-Operable awning clerestory windows used to allow heat to escape to the exterior through the chimney effect.

-Provide shading for at least 50% of east and west facades of homes using wood screens, light shelves and trees in the landscaping.

-Insulation installed in walls exposed to the sun, east and west facing walls.

-Radiant barriers and insulation installed in roof.

-Roof slope and orientation designed to house solar water heater collectors and future/optional photovoltaic array.

-Solar collectors installed on the south facing roof with a slope of 3:12, or 14.04 degrees.

Openings

-Operable casement windows located at body level and vented clerestory windows at roof level on north façade for ventilation.

-High performance glazing used on windows on all facades.

($SHGC \leq 0.27$, $U\text{-value} \leq 0.60$, $VT > 0.70$)

-Spaces with openings on adjacent walls, windows are located far apart and at a diagonal.

-Spaces with openings on same wall use appropriately spaced casement windows.

-Casement, awning and jalousie windows used for best control of air flow.

-Glazing area on the north and south facing walls of the building is at least 50% greater than the sum of the glazing area on the east and west facing walls.

-Light shelves used for diffused lighting and shading.

Water Heating and Conservation

-Solar/Electric water heater installed.

-1” pipe insulation installed on at least first 8’ of outlet pipe from water heater.

-Water heater located within 20’ pipe length of bathroom fixtures.

-Install solar water heater collectors on south facing 3:12 slope roof oriented within 15 degrees of true south.

-Bathroom fixtures installed to meet LEED credit for Very High Efficiency Fixtures and Fittings

 -Low flow shower heads and sink faucets installed (≤1.75 gpm).

 -Low flow lavatory faucets used (≤1.5 gpm).

 -Low flow toilets installed (≤1.1 gpf).

Electric Lighting

-Reflectors used in can fixtures to maximize available light.

-Dimmers installed in bedrooms where low light levels are appropriate.

-Windows designed to reduce need for electric lighting during the day.

-Compact fluorescent lamps substituted for incandescent lamps.

-Quiet exhaust fans installed in bathrooms in addition to natural ventilation through windows in all full bathrooms.

Appliances

-Provide microwave oven to reduce reliance on range.

-Energy efficient clothes dryer provided, vented directly outside.

-Exterior clothesline space provided to reduce reliance on electric dryer.

-Energy Star clothes washer provided.

-Energy Star dishwasher provided.

-Energy Star refrigerator-freezer provided.

# *CHAPTER 4 PASSIVE DESIGN FEATURES*

## ***4.1 BUILDING ORIENTATION***

A building's orientation with relation to the Cartesian coordinates will impact its ability to optimize passive cooling, natural ventilation and daylighting. Orienting buildings correctly on a site involves many factors: the local topography, the requirements of privacy, the views, the reduction of unwanted noise, and the climatic factors of wind direction and solar radiation. One of the building designer's tasks is to position a home to take full advantage of the sun's value for daylight, hygiene and psychological benefits. Generally it is best to elongate the building along the east-west axis. The shorter sides of the building should face east and west, and the longer sides should face north and south. The correct building orientation along the east-west axis is crucial to take advantage of daylight. Buildings will benefit more from the useable daylight entering the building from the north and the south. When light comes in through the east and west facing windows, the sun is low in the sky and creates a lot of glare and direct heat gain. It is more of a challenge to shade against the sun coming into the building from the east or the west facing sides of a building because of the low sun angle. The light that comes in through north facing windows for the majority of the year will be diffused or ambient because of the sun's position in the southern sky, which is the most suitable for daylighting. During the summer months the sun will reach the north side of a building in Hawai‘i, so it would be best to provide shading from roof overhangs to the windows on the north side to block direct heat gain. South facing windows are the most advantageous for transmitting daylight, but also the most vulnerable to heat gain as well.

In most equatorial locations, and especially near the equator, horizontal surfaces receive the greatest amount of direct sunlight. Twice as much solar radiation strikes horizontal surfaces, such as the roof, during the hottest times of day than vertical surfaces, such as walls. Horizontal and vertical surfaces can re-radiate a substantial amount of heat into the building depending on the reflectance and the emissivity of the material. At higher latitudes, vertical surfaces start receiving more direct sunlight, especially the walls that are facing the equator. The sunlight will also be more abundant on vertical surfaces in the winter when the sun is at a lower angle in the sky. In the summer, horizontal surfaces receive more sunlight because the sun is higher in the sky. It does not matter which climate the building is located in for window placement, north and south facing windows will be the most beneficial, while east and west facing windows will be the most troublesome. East and west-facing windows receive direct sunlight at the beginning and end of the day and need to be shaded using landscape elements, trellises, or shading devices to prevent direct sunlight and heat buildup in the interior. In lower latitudes, south windows should be well shaded by overhangs and shading devices as needed to keep the direct sunlight and the heat out during the day. Rooms requiring less light should be placed on the east and west sides of the building. The most important and occupied rooms like the kitchen, living room, and bedrooms should be placed along the north and south sides of the building.

The LEED for Homes rating system spells out good building orientation techniques for solar design. There is one credit available if the four following requirements are met:

a) The glazing area on the north- and south-facing walls of the building is at least 50% greater than the sum of the glazing area on the east- and west-facing walls.
b) The east-west axis of the building is within 15 degrees of due east-west.
c) The roof has a minimum of 450 square feet of south-facing area that is oriented appropriately for solar applications.
d) At least 90% of the glazing on the south-facing wall is completely shaded at noon on June 21 and unshaded at noon on December 21.

*LEED for Homes sets requirements for homes as national standards, which is not always beneficial to each location. For this project, having the south-facing windows unshaded at noon on December 21 would have a negative effect. In the cooling climate of Hawai‘i south-facing windows should be shaded at noon year round for effective cooling strategies.

The fact that each building has to achieve all four of these requirements in order to achieve one credit point means that these strategies are not hard to design for. These four requirements should be implemented into every building design whether or not the building is trying to achieve LEED certification. This is a good starting point for the beginning of the building and site designs. The fourth requirement, d), can be tested for in Ecotect to determine how much shading is required to maximize the interior comfort of the home.

The orientation of the building will be important to this project in a number of ways. One of the factors of orienting a building properly is designing the optimum window size and placement. Windows need to be properly designed to capture the prevailing breezes, direct them through the space, and let in as much daylight as feasible without allowing heat to infiltrate into the interior. Each of the buildings in the development will include solar water systems. Installing solar water heating systems is not expensive and will save the owners or users a substantial amount of money every month from their electric bills. Utilizing a solar water system in the home can cut monthly electric bills in half. The buildings will also be designed to incorporate photovoltaic systems as an optional upgrade to the home. Because this project is an affordable home project, it is not feasible to include a renewable energy system standard on each home. However, each home will be designed and oriented appropriately to house a photovoltaic system on the south-facing area of roof. Building orientation is the first step in successful solar design, followed by window selection, window placement, and shading techniques.

Each of the 21 buildings on the project site are oriented with the long axis of the home within the allowable 15 degrees of due east-west, except for one home. The home on lot 15 does not achieve this requirement due to the odd lot shape and location of the driveway entering into the carport. Incorporating the solar water heating system and photovoltaics will still be possible and effective, but at a lower efficiency than the buildings with preferable orientation. Absolute east –west orientation is ideal for shading and solar access, but it is not ideal for the trade winds in Hawai‘i. Having the long sides of the homes oriented at 15 degrees north of east will be the best orientation to capture the trade winds which come from the north-east most of the year (*see Figs. 4.1.1 – 4.1.5*).

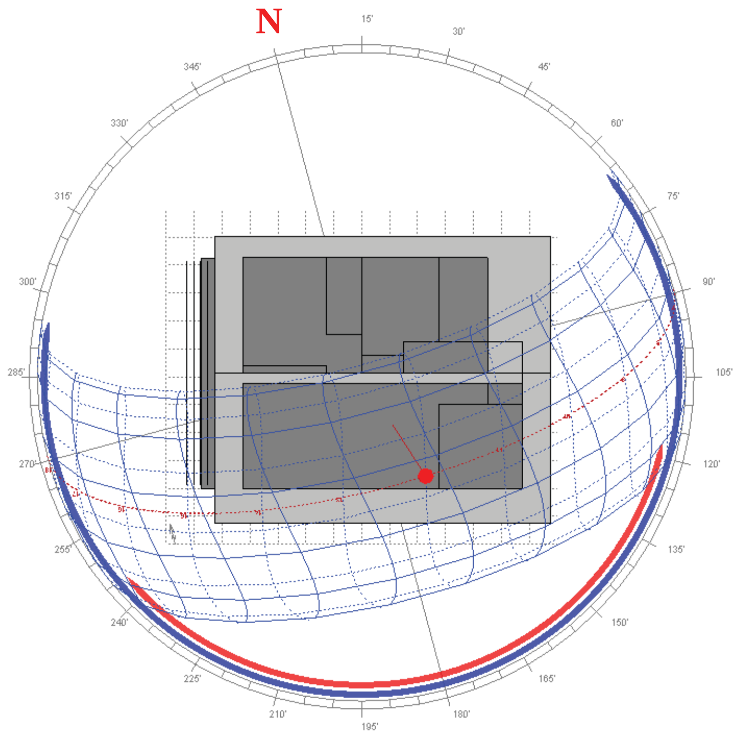



Fig. 4.1.1 - Annual sun path diagram showing the annual and daily sun path for September 21 at noon. The blue band at the bottom of the diagram shows the sun pattern for June 21st. The red band shows the sun pattern on December 21st.

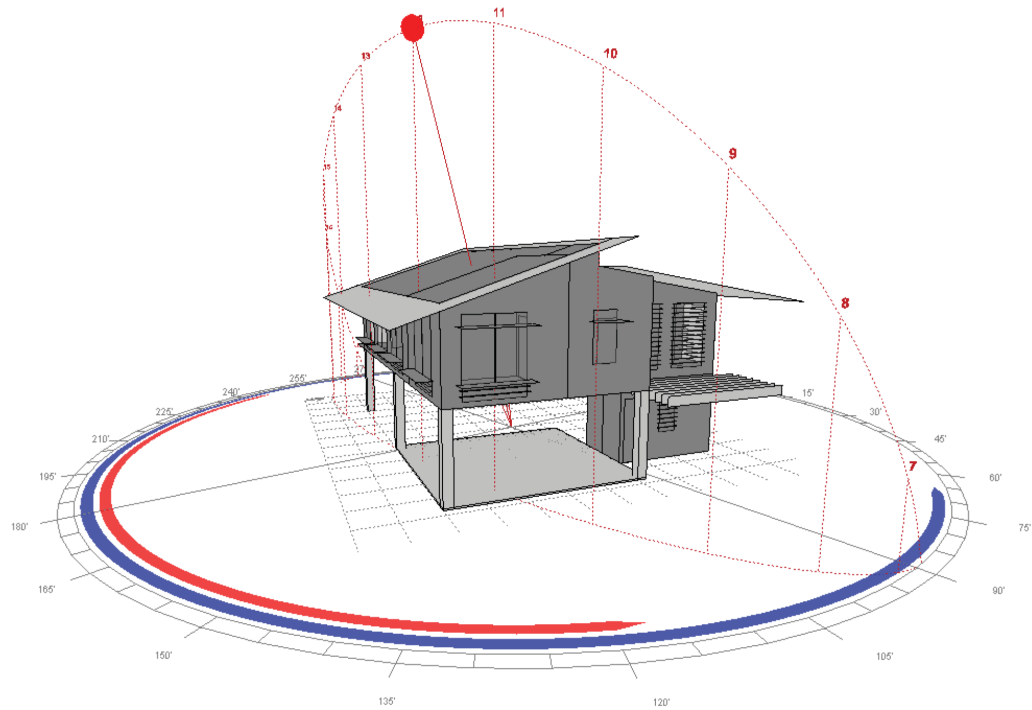


Fig. 4.1.2 - South-East view of house with the daily sun path for September 21 at noon.

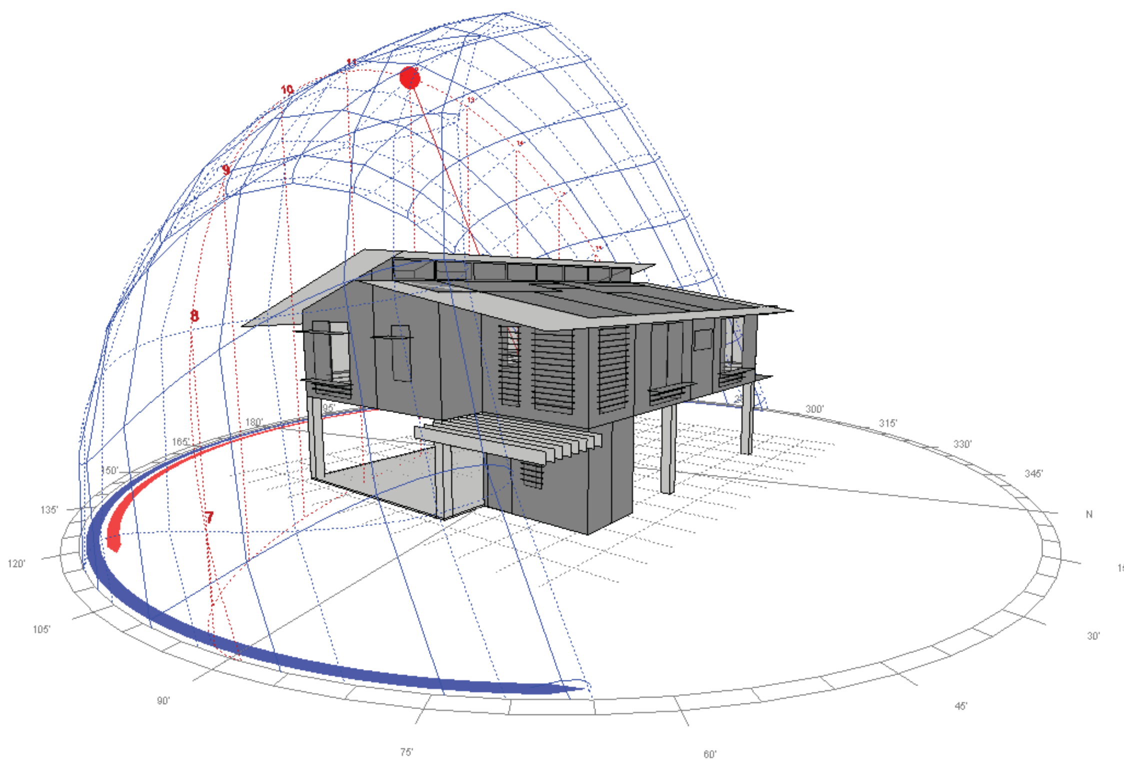


Fig. 4.1.3 - North-East view of house with the daily and yearly sun paths for September 21 at noon.

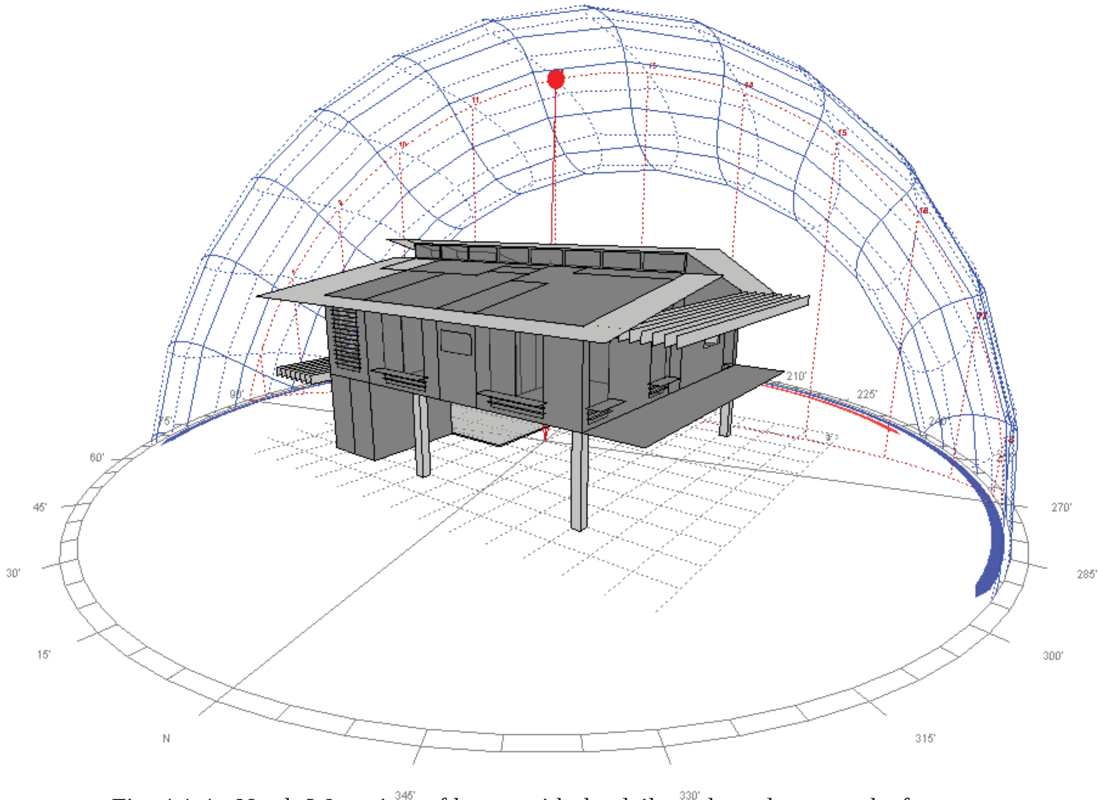



Fig. 4.1.4 - North-West view of house with the daily and yearly sun paths for September 21 at noon.

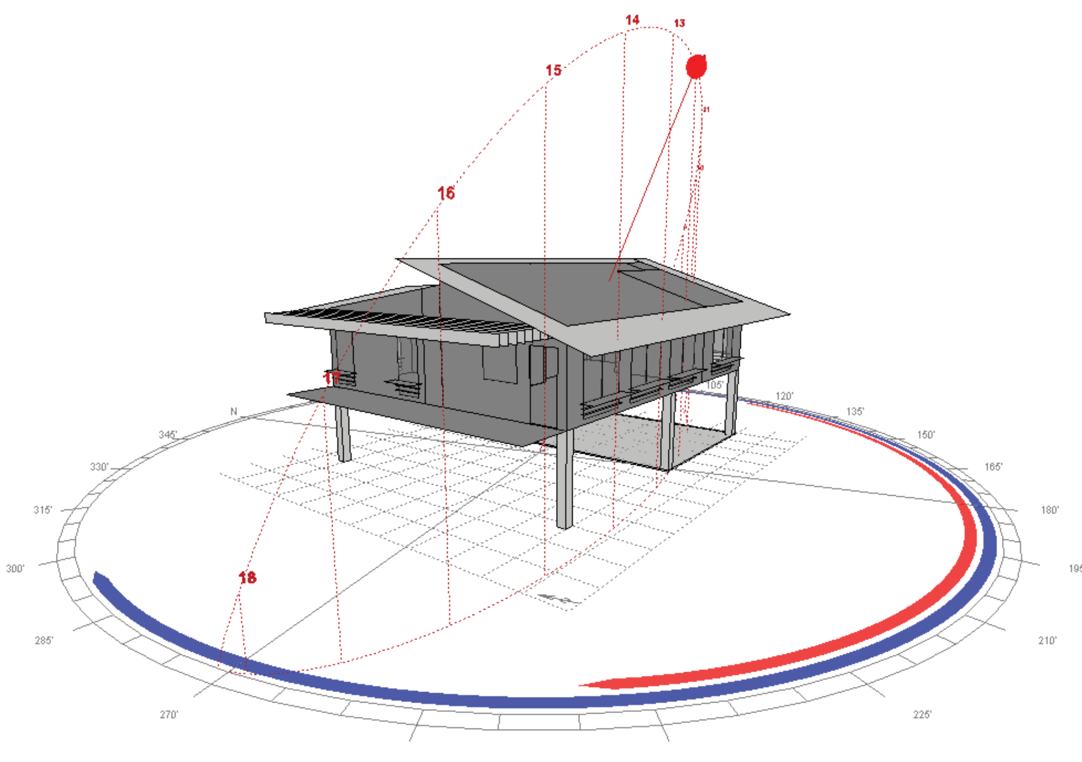



Fig. 4.1.5 - South-West view of house with the daily sun path for September 21 at noon.

## ***4.2 MITIGATING HEAT GAIN***

The most significant factor of heat gain in a building is from the radiant heat from the sun. At noon, the angle of the sun to where it touches the earth's surface is the most direct which will result in the greatest amount of insolation. Early in the morning and later in the afternoon, the angle of the sun to the point of impact on the earth is greater, resulting in less insolation received due to solar radiation spreading across a greater area. Heat buildup needs to be stopped before entering the building. Insulation, radiant barriers and shading devices can significantly reduce heat buildup and these will be the most effective building elements to mitigate internal heat gain. The main modes of heat transfer, conduction, convection and radiant heat transfer can be reduced through appropriate construction techniques and the right choice of building materials for the climate.

### 4.2a Heat Movement Physics

Heat moves from warmer materials to cooler ones until there is no longer a temperature difference between the two. The larger the difference between the temperatures, the faster the heat transfers. There are three ways that heat moves through space, buildings and materials: conduction, convection and radiation (*see Fig. 4.2.1*).

*Conduction* is the way heat moves through materials. Heat causes molecules close to the heat source to vibrate vigorously, and these vibrations spread to neighboring molecules, thus transferring heat energy. A good example of this would be a spoon placed into a hot cup of coffee. The spoon conducts heat through its handle and into the hand that grabs it.

*Convection* is the way heat circulates through liquids and gases. The lighter, warmer air rises as cooler, denser air falls. This is why attics are typically warmer than basements, which are generally much cooler.

*Radiant* heat moves through the air from warmer objects to cooler objects. Instead of rising like warm air, radiant heat works by heating the coldest and closest objects to the heat source. Any material with a temperature above absolute zero gives off some radiant energy. There are two types of radiation important to passive solar design, solar radiation and infrared radiation. When radiation strikes an object, it will do one or all of three things: be absorbed by the object, be reflected by it or be transmitted by it, depending on the object's properties (Passive Solar Design).

Radiant heat transfer takes place through five main channels: direct short-wave radiation from the sun, diffused short-wave radiation from the sky vault, short-wave radiation reflected from the surrounding terrain, long-wave radiation from the heated ground and nearby objects, and outgoing long-wave radiation exchange from the building to the sky. Before solar radiation can reach the ground it is reduced in intensity through the impurities in the air and partially absorbed by some atmospheric constituents such as carbon dioxide, water vapor and the ozone. Solar radiation is the most critical natural contributor to heat buildup in buildings. It is of primary interest to calculate the prevalence of solar radiation in order to design a building to prevent it from warming the interior.

Inside a home, infrared radiation occurs when warm surfaces radiate heat to cooler objects. Your body can radiate heat to a cooler surface, possibly causing you discomfort. The surfaces of a home that can radiate heat include walls, windows, floors, ceilings, roofs, furniture and appliances. Clear single pane glass can transmit up to 90% of solar radiation, which means that it will absorb and reflect 10% of the incoming solar radiation. After solar radiation is transmitted into the home, it is then absorbed and re-radiated from the interior surfaces as infrared radiation (Efficient Windows).

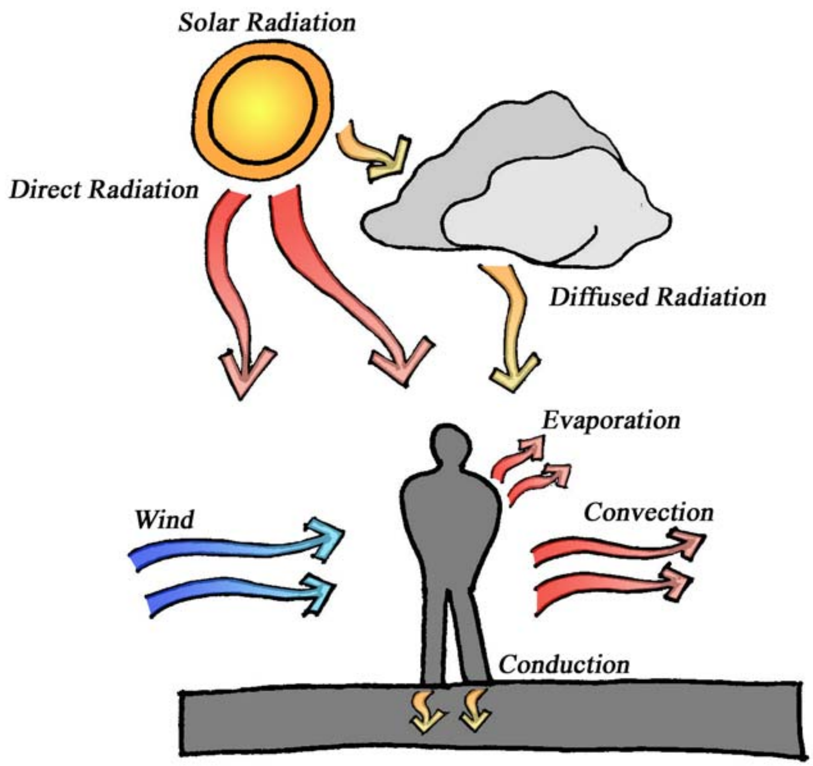



Fig. 4.2.1 Sources of solar heat transfer

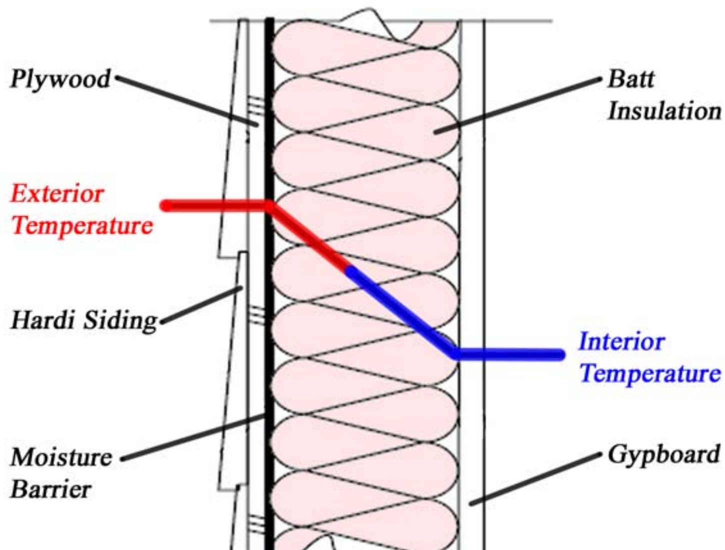



Fig. 4.2.2 Building section showing thermal insulation construction
*Source: Field Guide for Energy Performance, State of Hawaii*

## 4.2b Insulation

Insulation resists heat transfer by conduction through a building's walls, roofs and ceilings. Insulation cannot stop the transfer of heat through the building, only slow it. It may also slow the heat transfer by means of radiation and convection through walls and roofs (*see Fig. 4.2.2*). Insulation is now being made from recycled content such as slag, glass, paper fiber and plastics. It is available in several forms including rolls or batts, loose-fill, spray foam and rigid boards, some of which have structural and moisture barrier properties. The resistance value of insulation is the R-value. The higher the R-value of a material, the greater the material's ability is to resist heat transfer. Insulation should be installed in both the walls exposed to direct sunlight and roofs or attics of buildings in Hawaii.

The U.S. Department of Energy (USDOE) recommends insulating exterior walls in Hawai‘i with an R-value of R-13 to R-15. Walls are not required to be built with insulation for Hawai‘i, but it is recommended for any walls that will receive significant sunlight during the day, such as the east and west facing walls. Walls that are well shaded throughout the day do not require the added insulation to help mitigate heat, which will benefit from allowing the heat to be released at night. Insulation will also keep the heat from escaping at night, and therefore it would be beneficial to not insulate well shaded walls so that they may breathe better and help expel heat during the night. With the addition of a radiant barrier, the R-value of the insulation can be reduced; this applies to all insulated assemblies which may also include a radiant barrier. According to the USDOE the recommended R-value for a cathedral ceiling assembly in Hawai‘i is R-15 to R-22. Roof assemblies require a higher R-value than walls due to the increased amount of solar radiation that strikes it during the day. The roof is the greatest source of heat gain in buildings in Hawai‘i, due to the high angle of the sun throughout the year. On a clear day, the heat value, described as British thermal unit's (BTUs) from the sun vary from 0 BTUs/hour/sq. ft. at dawn to 300+ BTUs/hour/sq. ft. in the middle of the day (Roof Shade). This direct solar radiation will be absorbed by the roof and transferred into the home creating substantial temperature gains.

A well insulated building is one of the most effective ways of reducing the cooling load on the interior. West, south, and east facing walls receive a lot of solar radiation throughout the day. During the winter months in Hawai‘i, poorly shaded south facing walls can receive up to 1,300 Btu’s per square foot per day, which can create substantial radiant heat gain (State of Hawaii DBEDT, 39). Without insulation, many of the other energy efficient components won’t work as intended.

### 4.2c Radiant Barriers

Radiant barriers are thin sheets of highly reflective material that prevent heat buildup inside the building by reflecting the radiant heat back up away from the interior of the building instead of absorbing it. Radiant barriers usually consist of a thin sheet or coating of a highly reflective material, usually aluminum, applied to one or both sides of a number of substrate materials including craft paper, plastic films, cardboard, plywood sheathing and air infiltration barrier material. When installed, the reflective surface must be faced down and be installed next to a minimum ¾” open air space. If not, it will lose most of its effectiveness in reflecting radiant heat. They can be designed and installed to work with insulation to further control the thermal comfort indoors. A roof can reach a temperature of up to 150° F, even when the outdoor temperatures are only 80° F. Radiant barriers can reflect up to 95% of the sun’s radiant heat and significantly lower the ceiling temperatures of a building by more than 15° F, which in turn will lower the indoor air temperature (State of Hawaii DBEDT, 33). Some radiant barriers have insulating properties as well, but if they don’t they should be used in combination with insulation. Radiant barriers are rated based on their emissivity. The lower the emissivity rating, the more effective it is at reflecting radiant heat. Radiant barriers can be installed in walls, roofs and ceilings. They are most effective at reflecting the heat and lowering the interior temperature when installed on the roof or in an attic space (*see Figs. 4.2.3 – 4.2.4*).

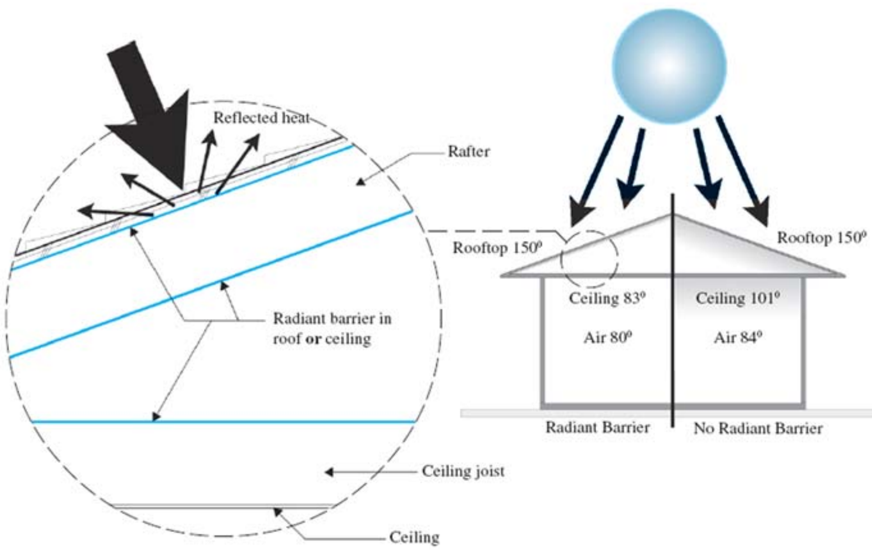



Fig. 4.2.3 Building section showing radiant barrier construction and advantages
*Source: Field Guide for Energy Performance, State of Hawaii*

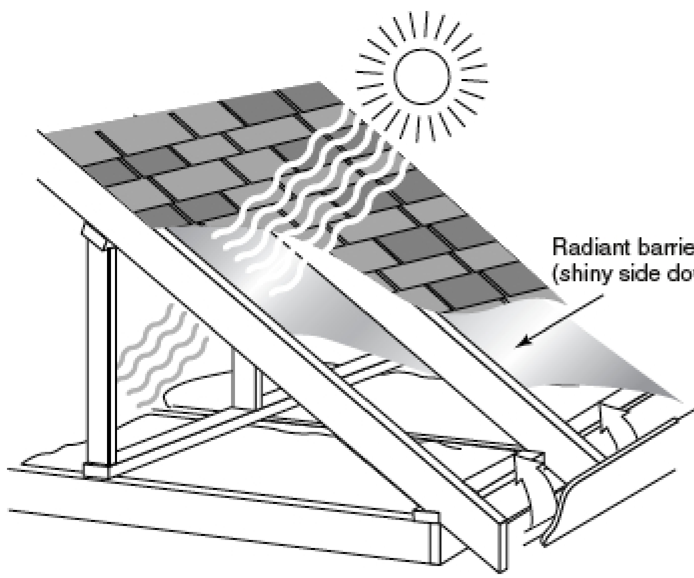



Fig. 4.2.4 Diagram showing radiant barrier placement in a roof
*Source: www.dropyourenergybill.com*

| NATURE OF SURFACE | ESTIMATE % REFLECTED |
| --- | --- |
| Bare ground, dry | 10–25 |
| Bare ground, wet | 8–9 |
| Sand, dry | 18–30 |
| Sand, wet | 9–18 |
| Mold, black, dry | 14 |
| Mold, black, wet | 8 |
| Rock | 12–15 |
| Dry grass | 32 |
| Green fields | 3–15 |
| Green leaves | 25–32 |
| Dark forest | 5 |
| Desert | 24–28 |
| Salt flats | 42 |
| Brick, depending on color | 23–48 |
| Asphalt | 15 |
| City area | 10 |

Fig. 4.2.5 Chart of Surface Reflectance from Exterior Elements
*Source: Design With Climate, Olgyay*

4.2d Building Materials

A building's materials will play an important part in the performance of the building. The reflectance value of a material can help mitigate unwanted heat gain. Materials that are lighter in color have a much higher reflectance percentage than darker colored materials. Solar radiation can even be reflected into buildings from landscaping materials such as grass, rock, sand and paving materials (*see Fig. 4.2.5*). Buildings must be designed with materials appropriate to the local climatic conditions to avoid heat buildup or loss. The two most important assemblies for a building regarding material selection are the roof and the walls.

The materials for this project were all chosen for their sustainable or efficient qualities. Each of the exterior materials mitigates heat gain to keep the interior naturally comfortable. The interior of the houses include materials made from recycled content and waste material, and also assist in keeping the interior cooler and brighter during the day. The colors are chosen to help reflect heat away on the exterior during the daytime, while the interior materials help reflect the daylight to maximize natural daylight thus minimizing electric lighting needs.

Concrete Floors-

Concrete floors are considered a sustainable flooring alternative and have many benefits over other typical flooring materials such as carpet, vinyl or wood floors. The benefits of concrete floors include: a wide variety of color and design options, excellent lifespan, very low maintenance requirements, invulnerability to humidity, moisture damage and mildew, and extremely low lifecycle cost. The average cost per square foot is slightly higher than carpet or vinyl/linoleum, but is still cheaper than ceramic tile, stone or wood flooring.

This project will use concrete as the floor material on the ground floor of each home. It would be too expensive and structurally challenging to install concrete floors on the second floor of the homes. Using concrete as flooring reduces the need for floor material changes over the building lifetime, and provides beautiful and cool floor surfaces. Concrete floors will also add thermal mass, which has the potential to increase heat buildup in the interior of the houses. When direct sunlight hits concrete it absorbs the heat, stores it and then releases the heat back into the building later. One of the challenges in using this material is to capture the cooling potential of the floors while reducing the heat buildup from added thermal mass. This can be accomplished by providing shading of the floor throughout the year, as well as adding floor coverings such as rugs, which is optional for the homeowner. The benefits of thermal mass in residential buildings include: delaying peak loads, reducing peak loads and potentially reducing overall load demand. Concrete floors have a wide variety of color, texture and design options for special and unique designs. For this project, the concrete will be left unstained but given a polish after it is set and dried to provide a smooth, glossy and unique look for these homes.

Cool Metal Roofing-

If designed properly using the right materials for the climate, roofs can assist in keeping the temperatures cooler in the interior of a building. In Hawaiʻi there is a need for the roof to mitigate heat gain in the interior spaces. Cool metal roofing will reflect a substantial amount of heat away from the building and the interior spaces. Cool roofs can save up to 40% in cooling energy, as reported by the Heat Island Group of Lawrence Berkeley National Laboratory. In addition to the cooling benefit of metal roofs there are also sustainable benefits. Metal roofs are typically built of a minimum 25% recycled material, and are 100% recyclable and reusable when renovating or demolishing a building. Other roofing products like tile and shingles are made of organic materials which are porous and can harbor mold and lead to degradation over time. Metal roofing is also more wind and fire resistant than shingle or tile roofs. All the benefits of metal roofing mean less maintenance and a longer lifespan. Using cool metal roofing will help contribute to Hawaii BuiltGreen and LEED points as well. Site-built homes also qualify for a $2,000 credit if they reduce energy consumption by 50% relative to the International Energy Conservation Code standard (HPM Building Supply).

The roof of this project will be constructed of standing seam metal. By definition from the ENERGY STAR website, the south facing 3:12 slope roof is considered a steep-slope roof, and the north facing 1:12 slope roof is considered a low-slope roof; each of the roofs have different cool roof rating requirements. By design, both sides of the roof will be constructed of the same material and color and therefore the roofing product and coatings chosen for this project will meet the requirements for the more stringent low-slope roof criteria. To be considered an ENERGY STAR cool roof, the initial solar reflectance of a low-slope roof must be greater than 0.65, which is much higher as compared to the steep-slope roof initial solar reflectance of 0.25. The impact the criteria has on the design is fewer choices in roofing color. Lighter color roofs typically have a higher solar reflectance than a darker color. Shades of white are the only colors available that meet the requirement of an initial solar reflectance greater than 0.65. The roof coating chosen for all homes in the development will be Dura Coat Products Ceranamel XT-40 in bright white, which has an initial solar reflectance of 0.75 and an initial thermal emissivity of 0.86. This product will qualify as an ENERGY STAR cool roof and also qualifies for the tax rebate.

Siding-

Horizontal lap siding is the material used for all the homes in the development. One of the industry leaders in sustainable siding products is James Hardie. Their siding offers sustainable benefits and, as they boast, extreme durability. HardiePlank Lap Siding comes in a variety of colors and styles to choose from. This project will use 9.25" smooth lap siding in a variety of light color tones to help give the houses more individuality. The HardieZone system engineers siding for the various climate zones. The HZ10 siding is designed to resist cracking, splitting, rotting and swelling for the hot, humid, salty and windy climate of Hawaiʻi.

4.2e Ecotect Thermal Analysis

Three models were designed and modeled in Ecotect to test and analyze thermal comfort, natural ventilation and daylighting levels. Each model has the same basic core; the size, shape, and floor plan of the houses are all exactly the same. The base case house model uses typical residential building materials found in Hawai‘i. The house is wood framed, the first floor is concrete slab on grade, the second floor is carpet over wood framing and the roof is asphalt shingles. The model conforms to the Federal and State buildings codes. The windows are designed as single glazed clear glass with a U-Factor of 1.16, an SHGC of 0.76 and a VT of 0.75. The window area is designed to the recommended low of 15% window to wall ratio (WWR). The roof overhangs on each side of the home is 3’.

The first green home is designed similar to the base case with a few material changes and increasing the window and roof areas. In this model the walls are designed with Hardie Siding on a wood frame and standing seam metal roofing. The windows on the east and west sides of the home have been designed as double glazed Low-E with a U-Factor of 0.34, an SHGC of 0.30 and a VT of 0.51. Clerestory windows have been added to the north facing wall in the kitchen/living area. The WWR has been increased in this model to 35%. The roof overhangs on the east and west sides of the home have been increased to 4’ and the roof overhangs on the south side have increased to 5’.

The final green home is derived from the first green home and has a few more changes to materials and window size and placement. In this model the east and west facing walls receive R-15 insulation. All windows in the model are designed as double glazed Low-E windows with a U-Factor of 0.29, an SHGC of 0.21 and a VT of 0.47, and have been increased to 40% WWR. The final additions to this model are wooden trellises over the lanai and front porch.

The tests performed in Ecotect for thermal comfort analysis include direct solar gains, discomfort degree hours, average daily radiation, interior versus exterior temperatures and annual temperature distribution.

The direct solar gains analysis is effective in seeing where and when direct sun is entering the interior, and where it will be most advantageous to shade windows and walls.

The greater the amount of direct solar gains, the warmer the interior will be. The goal is to design for as much window area as feasible for natural ventilation and daylighting, but keep them shaded to reduce the direct solar gains in the interior. The majority of the direct solar gains occur during the morning (7:00am – 9:00 am) and afternoon (4:00pm – 5:00pm) when the sun is low in the eastern and western sky. The final model receives significantly less direct gains due to increased shading of the windows and the use of low solar gain double glazed Low-E windows (*see Figs. 4.2.6 – 4.2.17*). The direct solar gains can be lowered even further with the addition of shading trees on the south-east and south-west sides of the home.

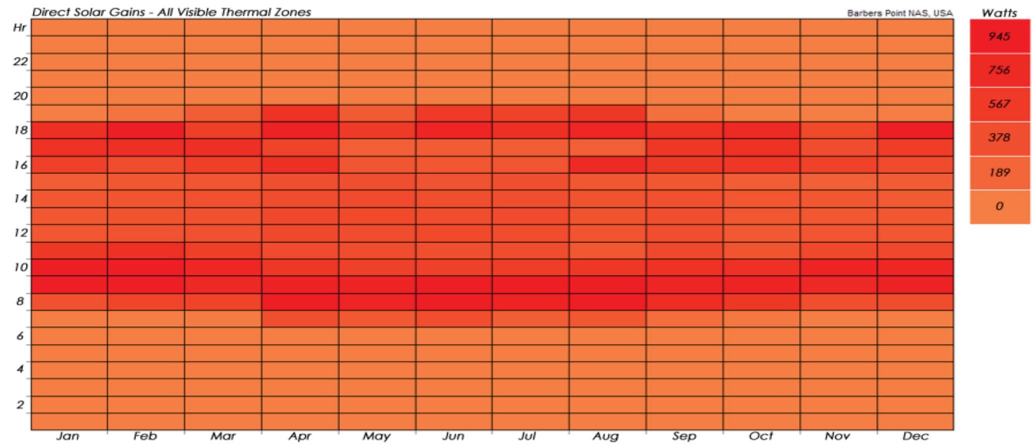



Fig. 4.2.6 - Graph showing the range of direct solar gains throughout the year for the final green house model for **ALL THERMAL ZONES**. The direct solar gains are expressed in Watts, with a range of 0 Watts (orange) to 945 Watts (red).

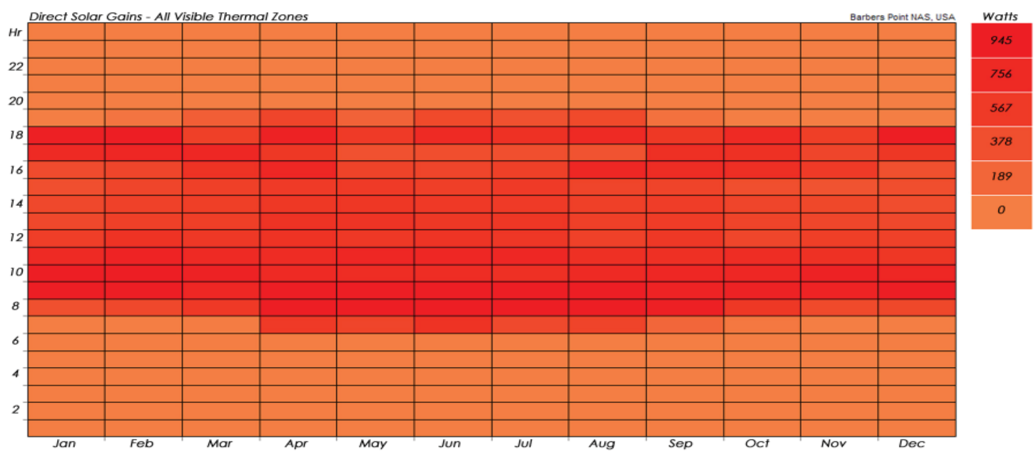



Fig. 4.2.7 - Graph showing the range of direct solar gains throughout the year for the first green house model for **ALL THERMAL ZONES**. The direct solar gains are expressed in Watts, with a range of 0 Watts (orange) to 945 Watts (red).

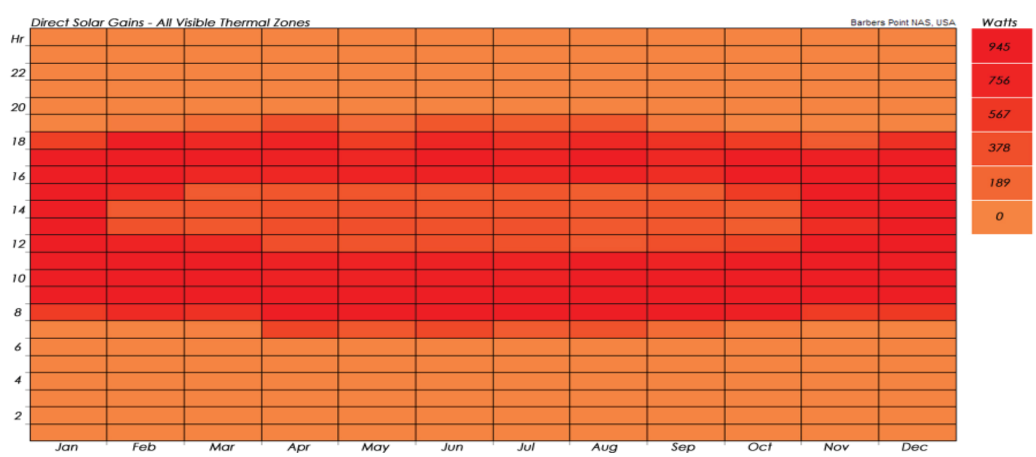



Fig. 4.2.8 - Graph showing the range of direct solar gains throughout the year for the base case house model for **ALL THERMAL ZONES**. The direct solar gains are expressed in Watts, with a range of 0 Watts (orange) to 945 Watts (red).

| ANNUAL LOADS TABLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direct Solar Gains - Qg | | | | | | | | | | | | |
| All Visible Thermal Zones - Monthly Averages | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| HOUR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) |
| 6 | 0 | 0 | 22 | 1281 | 988 | 1340 | 886 | 1031 | 435 | 128 | 0 | 0 |
| 7 | 1240 | 1576 | 1618 | 3258 | 2769 | 3737 | 2832 | 3254 | 2442 | 2008 | 1332 | 1356 |
| 8 | 3750 | 3242 | 2599 | 3062 | 2862 | 3848 | 3335 | 3752 | 2700 | 2820 | 2623 | 2947 |
| 9 | 3270 | 3249 | 2646 | 2009 | 1700 | 1699 | 1834 | 2054 | 2227 | 2277 | 2823 | 2655 |
| 10 | 1997 | 2317 | 1789 | 1407 | 1387 | 1304 | 1356 | 1011 | 1451 | 1119 | 1484 | 1475 |
| 11 | 1086 | 1173 | 1232 | 1454 | 1352 | 1442 | 1381 | 1126 | 1283 | 984 | 1153 | 1072 |
| 12 | 1002 | 1160 | 1196 | 1496 | 1432 | 1371 | 1397 | 1163 | 1270 | 1075 | 1038 | 1000 |
| 13 | 1002 | 1130 | 1219 | 1364 | 1402 | 1318 | 1289 | 1166 | 1232 | 1071 | 1019 | 929 |
| 14 | 864 | 1041 | 1149 | 1281 | 1309 | 1183 | 1277 | 1060 | 1078 | 883 | 789 | 902 |
| 15 | 1690 | 1386 | 1801 | 2389 | 1098 | 1070 | 1157 | 2538 | 1997 | 2042 | 1660 | 1418 |
| 16 | 2244 | 2397 | 2374 | 1623 | 818 | 898 | 882 | 823 | 2068 | 2230 | 1348 | 1843 |
| 17 | 2408 | 4116 | 1777 | 2997 | 1924 | 2697 | 2342 | 2670 | 2252 | 2559 | 1429 | 3205 |
| 18 | 0 | 229 | 864 | 2256 | 924 | 1906 | 1634 | 2015 | 388 | 0 | 0 | 0 |

Fig. 4.2.9 - Table showing the numerical values for direct solar gains throughout the year for the final green house model for **ALL THERMAL ZONES**. The direct solar heat gains are expressed in Btu's and shown as monthly averages. The highest monthly values range from 2,646 Btu's in March to 4,116 Btu's in February.

| ANNUAL LOADS TABLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direct Solar Gains - Qg | | | | | | | | | | | | |
| All Visible Thermal Zones - Monthly Averages | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| HOUR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) |
| 6 | 0 | 0 | 31 | 1949 | 1587 | 2219 | 1457 | 1619 | 611 | 156 | 0 | 0 |
| 7 | 1258 | 1491 | 1958 | 4761 | 4373 | 6006 | 4486 | 4985 | 3164 | 2044 | 1436 | 1520 |
| 8 | 4457 | 3211 | 2744 | 3388 | 3931 | 6506 | 5029 | 4569 | 2838 | 2972 | 2835 | 3280 |
| 9 | 3289 | 3389 | 2985 | 2529 | 2451 | 2437 | 2361 | 2495 | 2674 | 2666 | 3049 | 2743 |
| 10 | 2496 | 2866 | 2565 | 2489 | 2744 | 2656 | 2673 | 2328 | 2334 | 2440 | 2274 | 2096 |
| 11 | 1807 | 2220 | 1991 | 2232 | 2018 | 2152 | 2062 | 1685 | 1993 | 1549 | 1821 | 1687 |
| 12 | 1496 | 1731 | 1785 | 2233 | 2137 | 2046 | 2086 | 1736 | 1895 | 1605 | 1549 | 1492 |
| 13 | 1495 | 1687 | 1819 | 2035 | 2093 | 1967 | 1924 | 1740 | 1838 | 1599 | 1522 | 1387 |
| 14 | 1290 | 1554 | 1715 | 1913 | 1954 | 1766 | 1907 | 1582 | 1610 | 1318 | 1177 | 1346 |
| 15 | 1398 | 1556 | 2220 | 2732 | 1639 | 1598 | 1727 | 2668 | 2454 | 2401 | 1909 | 1262 |
| 16 | 2501 | 2739 | 2730 | 2045 | 1221 | 1341 | 1317 | 1179 | 2380 | 2299 | 1568 | 2071 |
| 17 | 3112 | 4934 | 1717 | 2952 | 1930 | 2549 | 2291 | 2556 | 2037 | 2564 | 1786 | 4184 |
| 18 | 0 | 241 | 856 | 1567 | 755 | 1436 | 1244 | 1430 | 338 | 0 | 0 | 0 |

Fig. 4.2.10 - Table showing the numerical values for direct solar gains throughout the year for the first green house model for **ALL THERMAL ZONES**. The highest monthly values range from 2,972 Btu's in October to 6,506 Btu's in June.

| ANNUAL LOADS TABLE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direct Solar Gains - Qg | | | | | | | | | | | | |
| All Visible Thermal Zones - Monthly Averages | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| HOUR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) | (Btu) |
| 6 | 0 | 0 | 21 | 1057 | 680 | 858 | 579 | 780 | 407 | 149 | 0 | 0 |
| 7 | 1759 | 2370 | 1883 | 3033 | 2154 | 2630 | 2045 | 2826 | 2588 | 2836 | 1769 | 1745 |
| 8 | 4498 | 4720 | 3596 | 4269 | 2907 | 3587 | 3261 | 4717 | 3966 | 3987 | 3457 | 3833 |
| 9 | 4959 | 4799 | 3819 | 2817 | 2777 | 2974 | 2823 | 3382 | 3118 | 3314 | 3921 | 3864 |
| 10 | 3161 | 3126 | 3143 | 2823 | 2740 | 2775 | 2670 | 3123 | 2683 | 3243 | 2678 | 2725 |
| 11 | 2631 | 2722 | 2411 | 1251 | 1163 | 1241 | 1189 | 969 | 1288 | 1467 | 1976 | 2009 |
| 12 | 794 | 1011 | 1029 | 1287 | 1232 | 1180 | 1203 | 1001 | 1093 | 926 | 777 | 660 |
| 13 | 668 | 972 | 1049 | 1173 | 1206 | 1134 | 1109 | 1003 | 1060 | 922 | 710 | 612 |
| 14 | 555 | 831 | 988 | 1103 | 1127 | 1018 | 1099 | 912 | 928 | 682 | 518 | 594 |
| 15 | 1710 | 1565 | 2048 | 2529 | 2743 | 2810 | 2540 | 2709 | 2276 | 2016 | 1548 | 1412 |
| 16 | 2283 | 2385 | 2429 | 2862 | 2529 | 3011 | 2714 | 3023 | 2193 | 2114 | 1332 | 1869 |
| 17 | 787 | 1852 | 1575 | 2762 | 1792 | 2535 | 2190 | 2485 | 1737 | 1093 | 493 | 968 |
| 18 | 0 | 88 | 377 | 1160 | 540 | 1063 | 917 | 1076 | 186 | 0 | 0 | 0 |

Fig. 4.2.11 - Table showing the numerical values for direct solar gains throughout the year for the base case house model for **ALL THERMAL ZONES**. The highest monthly values range from 2,907 Btu's in May to 4,959 Btu's in January.

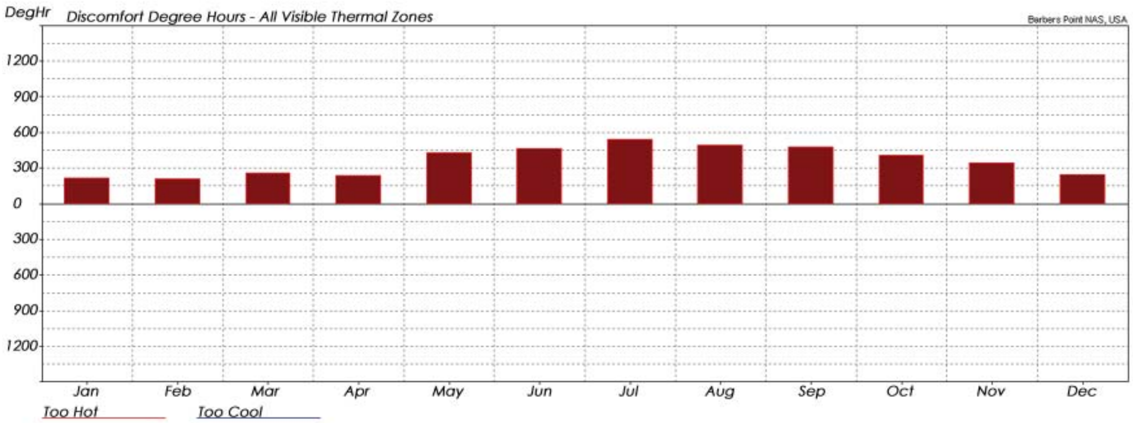



Fig. 4.2.12 - Graph showing the discomfort degree hours throughout the year for the final green house model for **ALL THERMAL ZONES**. The values are expressed in Degree Hours, and range from a low of 212 in February to a high of 540 in July.

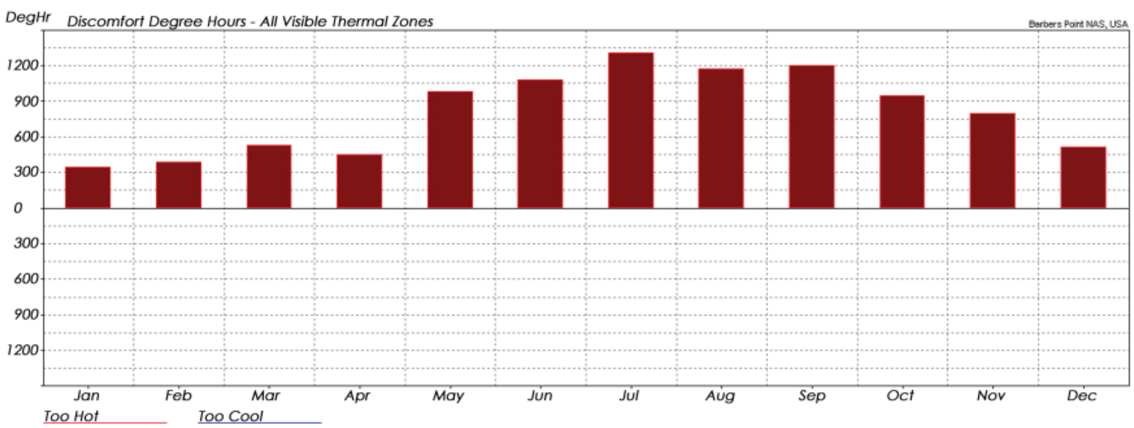



Fig. 4.2.13 - Graph showing the discomfort degree hours throughout the year for the base case house model for **ALL THERMAL ZONES**. The values for this model range from a low of 344 in January to a high of 1,309 in July.

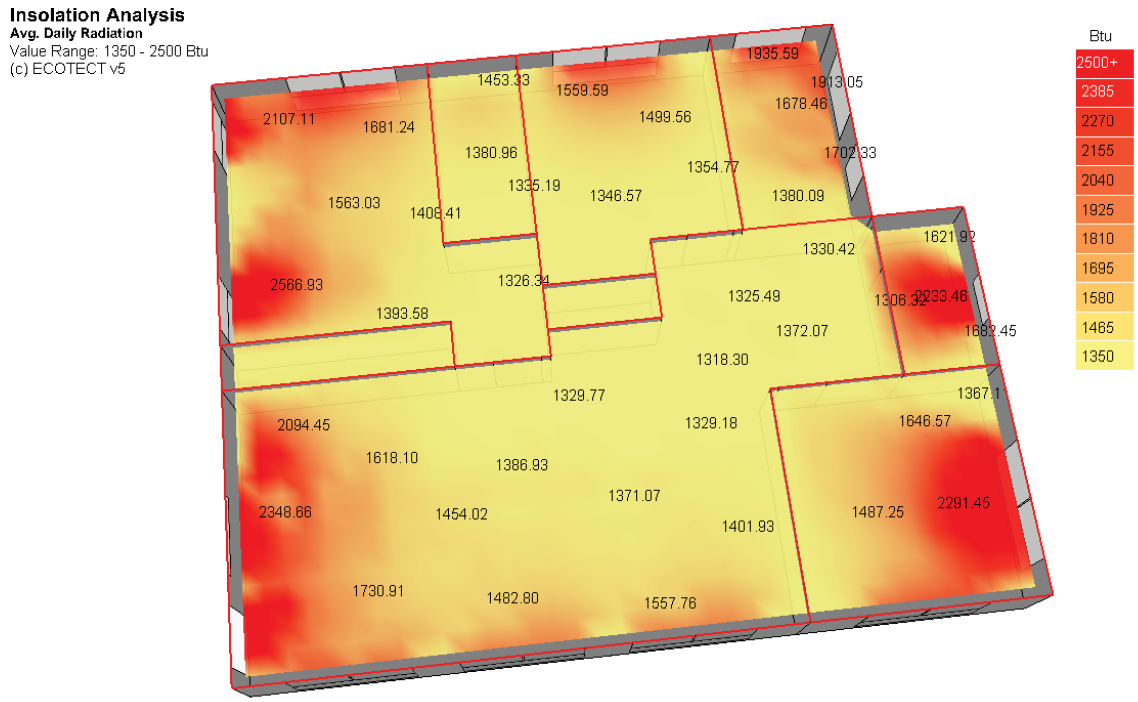



Fig. 4.2.14 - Perspective view of the final green house model showing the average daily radiation gains in Btu's. The values range from a low of 350 Btu's (yellow) to a high of 2,500 Btu's (red).

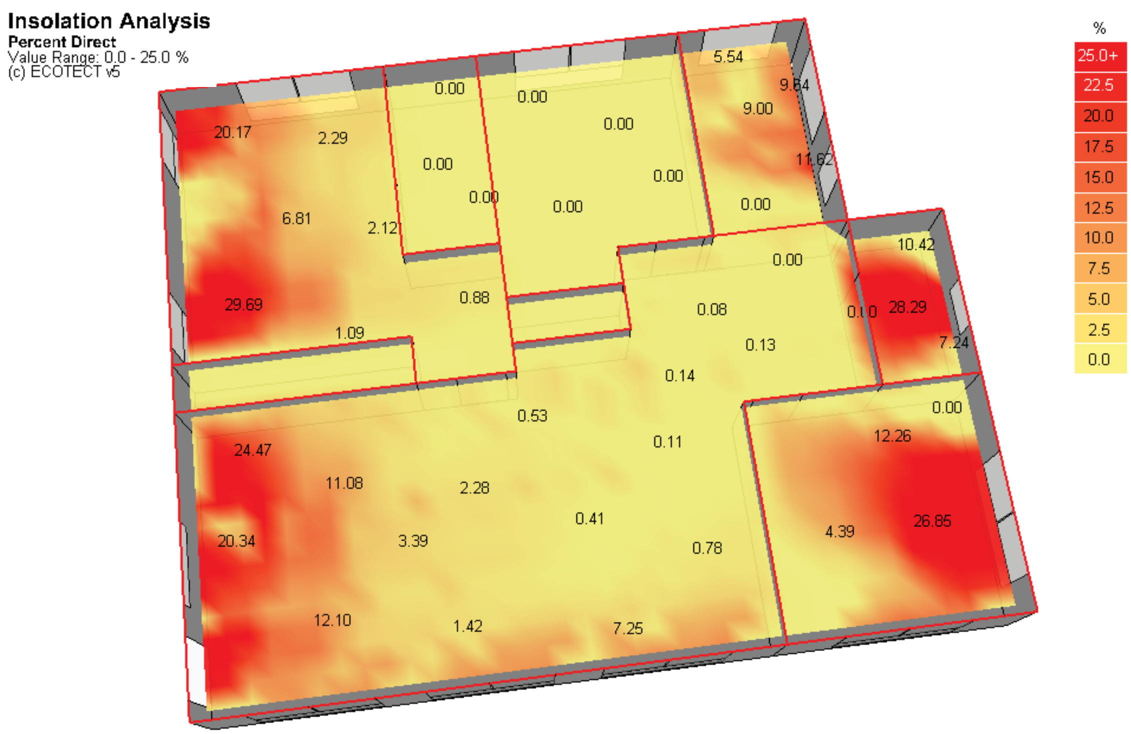



Fig. 4.2.15 - Perspective view of the final green house model showing the annual percentage of direct solar heat gains. The values for this model range from a low of 0% (yellow) to a high of 25% (red).

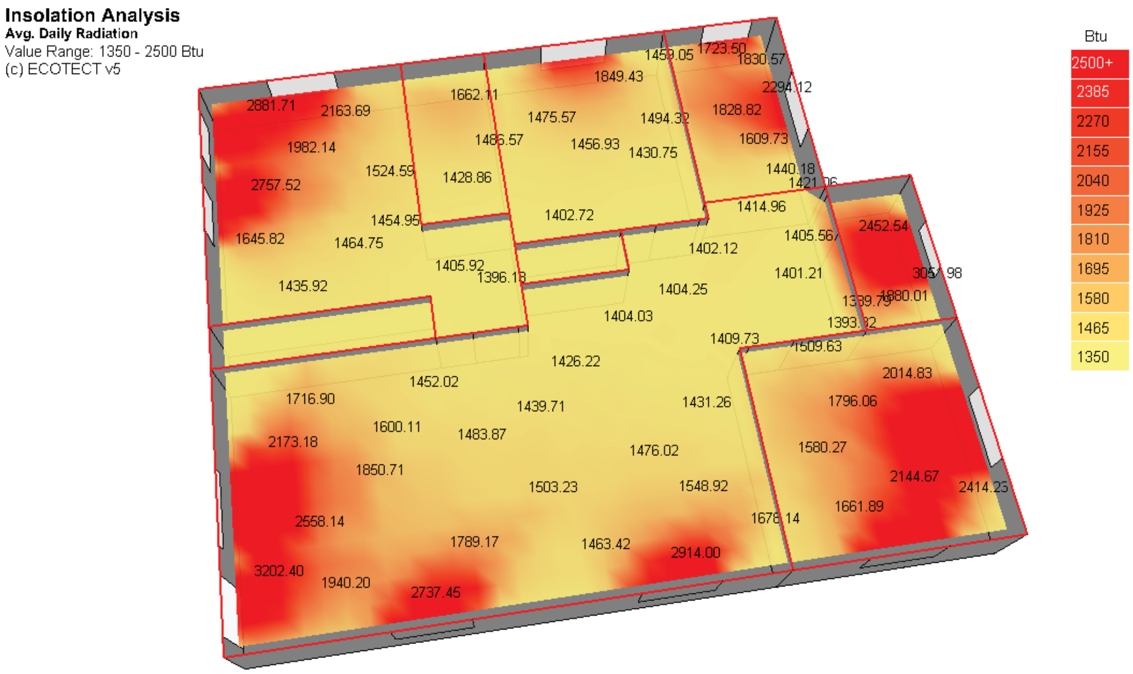



Fig. 4.2.16 - Perspective view of the base case house model showing the average daily radiation gains in Btu's. The values range from a low of 350 Btu's (yellow) to a high of 2,500 Btu's (red).

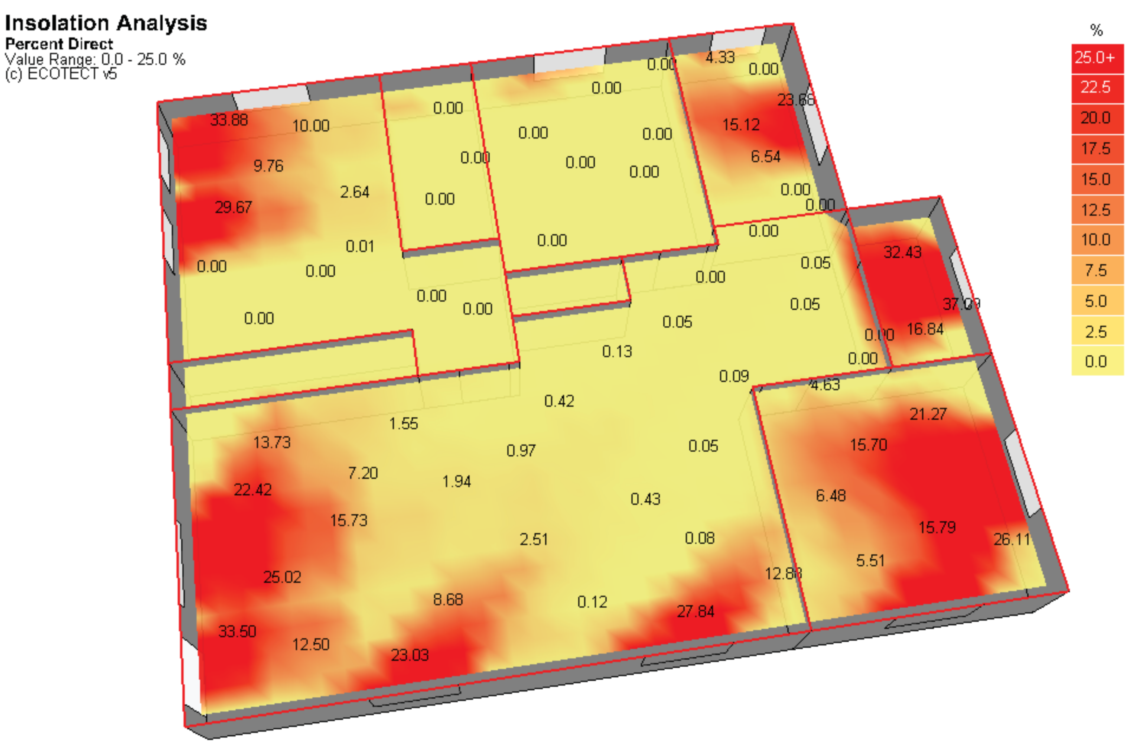



Fig. 4.2.17 - Perspective view of the base case house model showing the annual percentage of direct solar heat gains. The values for this model range from a low of 0% (yellow) to a high of 25% (red).

All three of the models are analyzed for hourly interior and exterior temperatures and the degree difference on the average coldest day of the year, January 31, and the average hottest day of the year, July 13. In addition the final green house model shows the hourly temperatures for the windiest day of the year, January 5, and the least windy day, December 10. The weather file used in Ecotect is for Barbers Point, Oahu, which is located about 5 miles south of the project site. This is the closest and most accurate data found for the specific site in Lualualei. The most important area of the house is the kitchen/living area. This space is the core of the house and is occupied more than the other spaces of the house. The temperature analysis is performed for the kitchen/living area for all three design models to show the overall improvement in thermal neutrality within the space (*see Figs. 4.2.18 – 4.2.27*).

The annual temperature distribution analysis shows the number of hours and percentage of interior temperature within the space. The analysis also shows the number of hours within and out of the natural comfort band. The comfort band for Hawai‘i is higher in temperature than the national average due to the difference in climate and the residents ability to adapt to the warmer weather. For this project the comfort band has been changed within Ecotect to a low of 71.4° F and a high of 83.8° F. The goal for this analysis is to get the interior temperatures to be within the comfort band throughout the year. The higher the percentage of temperatures within the comfort zone the more effective the thermal comfort design. The yearly temperatures for the base case house model kitchen/living area is within the comfort band 70.4%. The first green house model kitchen/living area is within the comfort band 70.1%. The percentage decrease is due to the large increase of window area and insufficient shading control. The final green house model increases the percentage within the comfort band to 78.5% of the year (*see Figs. 4.2.28 – 4.2.30*). Adding shading devices and using higher-performance windows for this model proves to be effective in providing better thermal comfort. Analysis was also conducted for the other spaces of the final green house model, which show higher percentages within the natural comfort band. The bedrooms show percentages within the comfort band of up to 88.1% of the year (*see Figs. 4.2.31 – 4.2.33*).

| HOUR | INSIDE | OUTSIDE | TEMP.DIF |
|---|---|---|---|
| | (F) | (F) | (F) |
| 0 | 61.7 | 55 | 6.6 |
| 1 | 61.2 | 54 | 7.2 |
| 2 | 60.7 | 54 | 6.7 |
| 3 | 59.8 | 52 | 7.8 |
| 4 | 59.6 | 52 | 7.6 |
| 5 | 59.4 | 52 | 7.5 |
| 6 | 60 | 54 | 6.1 |
| 7 | 64.4 | 68 | -3.6 |
| 8 | 66.5 | 68 | -1.5 |
| 9 | 70.1 | 73 | -3 |
| 10 | 72.3 | 75 | -2.7 |
| 11 | 76.4 | 79 | -2.6 |
| 12 | 78.5 | 79 | -0.5 |
| 13 | 79.9 | 79 | 0.9 |
| 14 | 79.4 | 79 | 0.4 |
| 15 | 77.4 | 75 | 2.4 |
| 16 | 75.1 | 73 | 2 |
| 17 | 74.4 | 72 | 2.5 |
| 18 | 69.8 | 70 | -0.2 |
| 19 | 67.1 | 64 | 3.1 |
| 20 | 65.9 | 63 | 3 |
| 21 | 65.7 | 63 | 2.7 |
| 22 | 65.5 | 63 | 2.5 |
| 23 | 64.9 | 63 | 2 |

Out of Comfort Zone 12am -10am

In Comfort Zone 10am - 6pm

Out of Comfort Zone 6pm -12pm

Fig. 4.2.18 - Hourly temperatures for the **KITCHEN-LIVING AREA** for January 31, the average coldest day of the year.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF |
|---|---|---|---|
| | (F) | (F) | (F) |
| 0 | 77.4 | 75.9 | 1.5 |
| 1 | 76.9 | 75 | 1.9 |
| 2 | 77.1 | 75.9 | 1.2 |
| 3 | 76.2 | 75 | 1.2 |
| 4 | 77.6 | 77 | 0.6 |
| 5 | 76.8 | 75.9 | 0.9 |
| 6 | 80.2 | 79 | 1.2 |
| 7 | 84.8 | 84 | 0.8 |
| 8 | 87.4 | 87.1 | 0.3 |
| 9 | 88.8 | 90 | -1.1 |
| 10 | 89.6 | 91 | -1.4 |
| 11 | 90.9 | 93 | -2.2 |
| 12 | 90.9 | 93.9 | -3.1 |
| 13 | 91.8 | 96.1 | -4.3 |
| 14 | 91.3 | 91.9 | -0.6 |
| 15 | 91.1 | 93.9 | -2.9 |
| 16 | 89.4 | 91 | -1.6 |
| 17 | 88.2 | 89.1 | -0.9 |
| 18 | 85.4 | 84 | 1.4 |
| 19 | 83.3 | 82 | 1.2 |
| 20 | 82.3 | 81 | 1.3 |
| 21 | 81.5 | 80.1 | 1.4 |
| 22 | 80.6 | 80.1 | 0.5 |
| 23 | 79.1 | 78.1 | 1.1 |

In Comfort Zone 12am -7am

Out of Comfort Zone 7am -7pm

In Comfort Zone 7pm -12pm

Fig. 4.2.19 - Hourly temperatures for the **KITCHEN-LIVING AREA** for July 13, the average hottest day of the year.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF |
|---|---|---|---|
| | (F) | (F) | (F) |
| 0 | 74.2 | 75.2 | -1 |
| 1 | 73.8 | 73.4 | 0.4 |
| 2 | 74.1 | 75.2 | -1.1 |
| 3 | 73.8 | 73.4 | 0.4 |
| 4 | 73.6 | 73.4 | 0.2 |
| 5 | 73.4 | 73.4 | 0 |
| 6 | 73.6 | 73.4 | 0.2 |
| 7 | 74.3 | 73 | 1.3 |
| 8 | 75.5 | 75.2 | 0.3 |
| 9 | 76.6 | 77.5 | -0.9 |
| 10 | 78.2 | 78.8 | -0.6 |
| 11 | 78.8 | 78.8 | 0 |
| 12 | 77.9 | 78.8 | -0.9 |
| 13 | 75.8 | 73.4 | 2.4 |
| 14 | 75.2 | 73.4 | 1.8 |
| 15 | 74.8 | 73.4 | 1.4 |
| 16 | 73.9 | 71.6 | 2.3 |
| 17 | 72.4 | 71.6 | 0.8 |
| 18 | 72.9 | 71.6 | 1.3 |
| 19 | 72.9 | 69.8 | 3.1 |
| 20 | 72.6 | 69.8 | 2.8 |
| 21 | 72.3 | 71.6 | 0.7 |
| 22 | 72.4 | 71.6 | 0.8 |
| 23 | 72 | 71.6 | 0.4 |

In Comfort Zone 12am - 12pm

Fig. 4.2.20 - Hourly temperatures for the **KITCHEN-LIVING AREA** for December 10, the average least windy day of the year.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF |
|---|---|---|---|
| | (F) | (F) | (F) |
| 0 | 71.9 | 72 | 0 |
| 1 | 71.9 | 72 | 0 |
| 2 | 72.5 | 73 | -0.5 |
| 3 | 72.6 | 73 | -0.4 |
| 4 | 72.6 | 73 | -0.4 |
| 5 | 72.6 | 73 | -0.4 |
| 6 | 72.7 | 73 | -0.3 |
| 7 | 73.4 | 73 | 0.3 |
| 8 | 75.2 | 75 | 0.2 |
| 9 | 77.3 | 77 | 0.3 |
| 10 | 76.7 | 75 | 1.7 |
| 11 | 75.4 | 73 | 2.4 |
| 12 | 75.5 | 73 | 2.4 |
| 13 | 76.5 | 75 | 1.5 |
| 14 | 74.9 | 75 | -0.2 |
| 15 | 74.9 | 75 | -0.1 |
| 16 | 75 | 74.5 | 0.5 |
| 17 | 73.5 | 73 | 0.5 |
| 18 | 73.7 | 73 | 0.7 |
| 19 | 71.5 | 66 | 5.5 |
| 20 | 70.9 | 66 | 4.9 |
| 21 | 71.4 | 68 | 3.4 |
| 22 | 71.9 | 70 | 1.9 |
| 23 | 71.4 | 70 | 1.4 |

In Comfort Zone 12am -8pm

Out of Comfort Zone 8pm

In Comfort Zone

Fig. 4.2.21 - Hourly temperatures for the **KITCHEN-LIVING AREA** for January 05, the average windiest day of the year.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF | |
|---|---|---|---|---|
| | (F) | (F) | (F) | |
| 0 | 59.4 | 55 | 4.3 | Out of Comfort Zone 12am -9am |
| 1 | 58.9 | 54 | 5 | |
| 2 | 58.7 | 54 | 4.7 | |
| 3 | 57.9 | 52 | 5.9 | |
| 4 | 57.5 | 52 | 5.5 | |
| 5 | 57.5 | 52 | 5.5 | |
| 6 | 58.3 | 54 | 4.3 | |
| 7 | 64.3 | 68 | -3.7 | |
| 8 | 68.3 | 68 | 0.3 | |
| 9 | 72.3 | 73 | -0.8 | In Comfort Zone 9am - 6pm |
| 10 | 75.3 | 75 | 0.3 | |
| 11 | 78.8 | 79 | -0.2 | |
| 12 | 81.4 | 79 | 2.5 | |
| 13 | 82.5 | 79 | 3.5 | |
| 14 | 81.7 | 79 | 2.7 | |
| 15 | 78.8 | 75 | 3.8 | |
| 16 | 75.7 | 73 | 2.7 | |
| 17 | 75.7 | 72 | 3.7 | |
| 18 | 69.3 | 70 | -0.7 | Out of Comfort Zone 6pm -12pm |
| 19 | 66.2 | 64 | 2.1 | |
| 20 | 64.5 | 63 | 1.5 | |
| 21 | 64.2 | 63 | 1.3 | |
| 22 | 64.2 | 63 | 1.3 | |
| 23 | 64.2 | 63 | 1.3 | |

Fig. 4.2.22 - Hourly temperatures for the first green house model **KITCHEN-LIVING AREA** for January 31.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF | |
|---|---|---|---|---|
| | (F) | (F) | (F) | |
| 0 | 75.9 | 75.9 | 0 | In Comfort Zone 12am -7am |
| 1 | 75.3 | 75 | 0.3 | |
| 2 | 75.7 | 75.9 | -0.2 | |
| 3 | 74.8 | 75 | -0.2 | |
| 4 | 76.4 | 77 | -0.6 | |
| 5 | 75.7 | 75.9 | -0.2 | |
| 6 | 79.8 | 79 | 0.8 | |
| 7 | 85.9 | 84 | 1.9 | Out of Comfort Zone 7am -7pm |
| 8 | 89 | 87.1 | 1.9 | |
| 9 | 91.2 | 90 | 1.2 | |
| 10 | 92.2 | 91 | 1.2 | |
| 11 | 93.3 | 93 | 0.2 | |
| 12 | 93 | 93.9 | -0.9 | |
| 13 | 94.1 | 96.1 | -2 | |
| 14 | 93.4 | 91.9 | 1.4 | |
| 15 | 92.5 | 93.9 | -1.4 | |
| 16 | 90.5 | 91 | -0.5 | |
| 17 | 88.4 | 89.1 | -0.7 | |
| 18 | 85.1 | 84 | 1.1 | |
| 19 | 81.9 | 82 | -0.2 | In Comfort Zone 7pm -12pm |
| 20 | 80.9 | 81 | -0.1 | |
| 21 | 80.1 | 80.1 | 0 | |
| 22 | 79.5 | 80.1 | -0.6 | |
| 23 | 78 | 78.1 | -0.1 | |

Fig. 4.2.23 - Hourly temperatures for the first green house model **KITCHEN-LIVING AREA** for July 13.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF | |
|---|---|---|---|---|
| | (F) | (F) | (F) | |
| 0 | 60.6 | 55 | 5.5 | Out of Comfort Zone 12am -9am |
| 1 | 60.1 | 54 | 6.2 | |
| 2 | 59.8 | 54 | 5.9 | |
| 3 | 59.1 | 52 | 7.1 | |
| 4 | 58.7 | 52 | 6.7 | |
| 5 | 58.6 | 52 | 6.7 | |
| 6 | 59.4 | 54 | 5.4 | |
| 7 | 65.5 | 68 | -2.5 | |
| 8 | 69.6 | 68 | 1.6 | |
| 9 | 73.1 | 73 | 0 | In Comfort Zone 9am - 6pm |
| 10 | 75.6 | 75 | 0.6 | |
| 11 | 78.5 | 79 | -0.5 | |
| 12 | 82 | 79 | 3 | |
| 13 | 81.1 | 79 | 2.1 | |
| 14 | 82.5 | 79 | 3.5 | |
| 15 | 80.6 | 75 | 5.6 | |
| 16 | 78.1 | 73 | 5.1 | |
| 17 | 75.2 | 72 | 3.2 | |
| 18 | 70.5 | 70 | 0.5 | Out of Comfort Zone 6pm -12pm |
| 19 | 67.4 | 64 | 3.4 | |
| 20 | 65.6 | 63 | 2.7 | |
| 21 | 65.4 | 63 | 2.4 | |
| 22 | 65.4 | 63 | 2.4 | |
| 23 | 65.4 | 63 | 2.4 | |

Fig. 4.2.24 - Hourly temperatures for the base case house model **KITCHEN-LIVING AREA** for January 31.

| HOUR | INSIDE | OUTSIDE | TEMP.DIF | |
|---|---|---|---|---|
| | (F) | (F) | (F) | |
| 0 | 78.5 | 75.9 | 2.6 | In Comfort Zone 12am -7am |
| 1 | 78 | 75 | 3 | |
| 2 | 78.3 | 75.9 | 2.4 | |
| 3 | 77.8 | 75 | 2.7 | |
| 4 | 78.9 | 77 | 1.9 | |
| 5 | 78.5 | 75.9 | 2.6 | |
| 6 | 81.6 | 79 | 2.7 | |
| 7 | 86.9 | 84 | 2.9 | Out of Comfort Zone 7am -7pm |
| 8 | 90.7 | 87.1 | 3.6 | |
| 9 | 92.8 | 90 | 2.8 | |
| 10 | 93.8 | 91 | 2.8 | |
| 11 | 94.8 | 93 | 1.7 | |
| 12 | 94.6 | 93.9 | 0.6 | |
| 13 | 95.6 | 96.1 | -0.5 | |
| 14 | 95 | 91.9 | 3.1 | |
| 15 | 94.4 | 93.9 | 0.4 | |
| 16 | 92.9 | 91 | 1.8 | |
| 17 | 90.8 | 89.1 | 1.8 | |
| 18 | 87.1 | 84 | 3.1 | |
| 19 | 83.7 | 82 | 1.7 | In Comfort Zone 7pm -12pm |
| 20 | 82.8 | 81 | 1.8 | |
| 21 | 82.1 | 80.1 | 2 | |
| 22 | 81.6 | 80.1 | 1.6 | |
| 23 | 80.5 | 78.1 | 2.4 | |

Fig. 4.2.25 - Hourly temperatures for the base case house model **KITCHEN-LIVING AREA** for July 13.

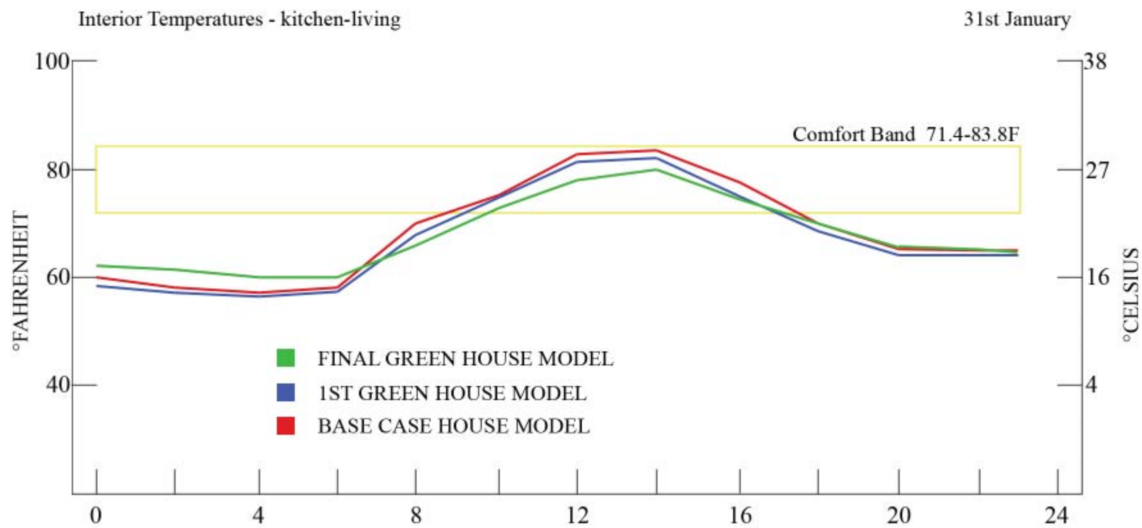



Fig. 4.2.26 - Hourly interior temperature graph for the **KITCHEN-LIVING AREA** for January 31, the average coldest day of the year. The graph shows that final model brings the temperatures closer to being thermally neutral than the original base case model. The final model has temperatures cooler than the comfort band for most of the morning and night.

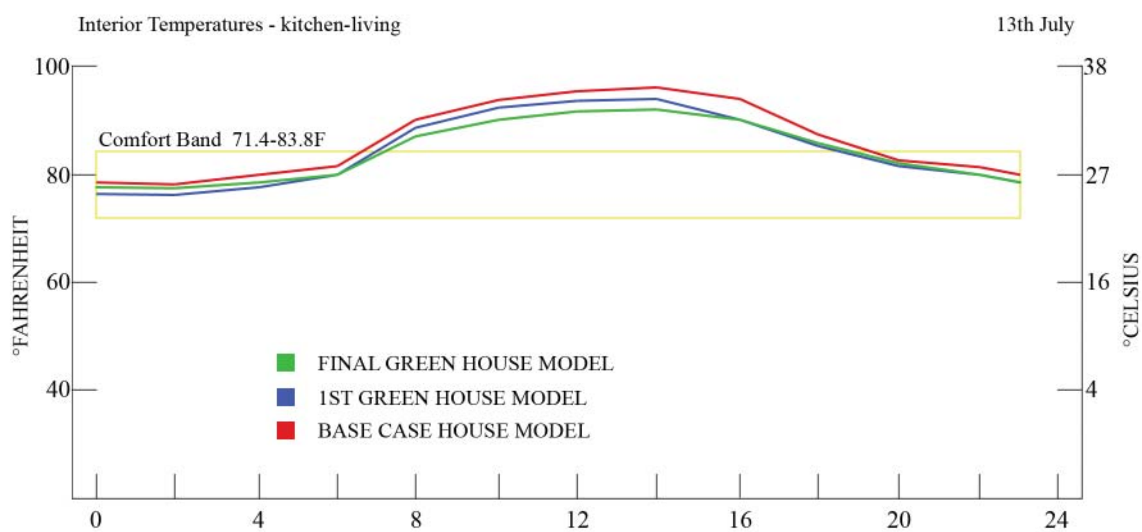



Fig. 4.2.27 - Hourly interior temperatures graph for the **KITCHEN-LIVING AREA** for July 13, the average hottest day of the year. The graph shows that final model brings the temperatures closer to being thermally neutral than the original base case model. Through the manipulation of the materials and elements of the final model the hourly temperatures have reached closer to the comfort band and has less temperature extremes. The final green house model has better thermal tollerance as compared to the base case model.

| ANNUAL TEMPERATURE DISTRIBUTION | | | |
|---|---|---|---|
| | | | |
| kitchen - living | | | |
| Operation: Weekdays 00-24, Weekends 00-24. | | | |
| Comfort Band: 71.4 - 83.8 F | | | |
| In Comfort: 6879 Hrs (78.5%) | | | |
| | | | |
| TEMP. | HOURS | PERCENT | |
| 53.6 | 0 | 0.00% | |
| 57.2 | 4 | 0.00% | Too Cool 13.8% |
| 60.8 | 65 | 0.70% | |
| 64.4 | 389 | 4.40% | |
| 68 | 754 | 8.60% | |
| 71.6 | 1886 | 21.50% | Comfort Zone 78.5% |
| 75.2 | 2158 | 24.60% | |
| 78.8 | 1657 | 18.90% | |
| 82.4 | 1178 | 13.40% | |
| 86 | 603 | 6.90% | Too Warm 7.7% |
| 89.6 | 65 | 0.70% | |
| 93.2 | 1 | 0.00% | |
| 96.8 | 0 | 0.00% | |
| COMFORT | 6879 | 78.50% | |

Temperature Range

Fig. 4.2.28 - Annual temperature distribution data table for the final green house model **KITCHEN-LIVING AREA**. This space is within the comfort band 78.5% of the year.

| ANNUAL TEMPERATURE DISTRIBUTION | | | |
|---|---|---|---|
| | | | |
| kitchen - living(1) | | | |
| Operation: Weekdays 00-24, Weekends 00-24. | | | |
| Comfort Band: 71.4 - 83.8 F | | | |
| In Comfort: 6142 Hrs (70.1%) | | | |
| | | | |
| TEMP. | HOURS | PERCENT | |
| 53.6 | 0 | 0.00% | |
| 57.2 | 21 | 0.20% | Too Cool 17.4% |
| 60.8 | 134 | 1.50% | |
| 64.4 | 495 | 5.70% | |
| 68 | 872 | 10.00% | |
| 71.6 | 1842 | 21.00% | Comfort Zone 70.1% |
| 75.2 | 1907 | 21.80% | |
| 78.8 | 1251 | 14.30% | |
| 82.4 | 1142 | 13.00% | |
| 86 | 824 | 9.40% | Too Warm 12.5% |
| 89.6 | 244 | 2.80% | |
| 93.2 | 28 | 0.30% | |
| 96.8 | 0 | 0.00% | |
| COMFORT | 6142 | 70.10% | |

Temperature Range

Fig. 4.2.29 - Annual temperature distribution data table for the first green house model **KITCHEN-LIVING AREA**. This space is within the comfort band 70.1% of the year.

| ANNUAL TEMPERATURE DISTRIBUTION | | | |
|---|---|---|---|
| | | | |
| kitchen - living(1) | | | |
| Operation: Weekdays 00-24, Weekends 00-24. | | | |
| Comfort Band: 71.4 - 83.8 F | | | |
| In Comfort: 6170 Hrs (70.4%) | | | |
| | | | |
| TEMP. | HOURS | PERCENT | |
| 53.6 | 0 | 0.00% | |
| 57.2 | 7 | 0.10% | Too Cool 11.9% |
| 60.8 | 74 | 0.80% | |
| 64.4 | 364 | 4.20% | |
| 68 | 594 | 6.80% | |
| 71.6 | 1500 | 17.10% | Comfort Zone 70.4% |
| 75.2 | 1874 | 21.40% | |
| 78.8 | 1624 | 18.50% | |
| 82.4 | 1172 | 13.40% | |
| 86 | 914 | 10.40% | Too Warm 17.6% |
| 89.6 | 552 | 6.30% | |
| 93.2 | 82 | 0.90% | |
| 96.8 | 3 | 0.00% | |
| 100.4 | 0 | 0.00% | |
| COMFORT | 6170 | 70.40% | |

Temperature Range

Fig. 4.2.30 - Annual temperature distribution data table for the base case house model **KITCHEN-LIVING AREA**. This space is within the comfort band 70.4% of the year.

| ANNUAL TEMPERATURE DISTRIBUTION | | |
|---|---|---|
| | | |
| bed 2 | | |
| Operation: Weekdays 00-24, Weekends 00-24. | | |
| Comfort Band: 71.4 - 83.8 F | | |
| In Comfort: 7487 Hrs (85.5%) | | |
| | | |
| TEMP. | HOURS | PERCENT |
| 53.6 | 0 | 0.00% |
| 57.2 | 0 | 0.00% |
| 60.8 | 26 | 0.30% |
| 64.4 | 274 | 3.10% |
| 68 | 708 | 8.10% |
| 71.6 | 1681 | 19.20% |
| 75.2 | 2228 | 25.40% |
| 78.8 | 2166 | 24.70% |
| 82.4 | 1412 | 16.10% |
| 86 | 262 | 3.00% |
| 89.6 | 3 | 0.00% |
| 93.2 | 0 | 0.00% |
| 96.8 | 0 | 0.00% |
| COMFORT | 7487 | 85.50% |

Temperature Range

Too Cool 11.4%

Comfort Zone 85.5%

Too Warm 3.1%

Fig. 4.2.31 - Annual temperature distribution data table for the final green house model **BEDROOM 2**. This space is within the comfort band 85.5% of the year.

| ANNUAL TEMPERATURE DISTRIBUTION | | |
|---|---|---|
| | | |
| bed 3 | | |
| Operation: Weekdays 00-24, Weekends 00-24. | | |
| Comfort Band: 71.4 - 83.8 F | | |
| In Comfort: 7717 Hrs (88.1%) | | |
| | | |
| TEMP. | HOURS | PERCENT |
| 53.6 | 0 | 0.00% |
| 57.2 | 0 | 0.00% |
| 60.8 | 9 | 0.10% |
| 64.4 | 245 | 2.80% |
| 68 | 685 | 7.80% |
| 71.6 | 2190 | 25.00% |
| 75.2 | 2181 | 24.90% |
| 78.8 | 1803 | 20.60% |
| 82.4 | 1543 | 17.60% |
| 86 | 104 | 1.20% |
| 89.6 | 0 | 0.00% |
| 93.2 | 0 | 0.00% |
| 96.8 | 0 | 0.00% |
| COMFORT | 7717 | 88.10% |

Temperature Range

Too Cool 10.7%

Comfort Zone 88.1%

Too Warm 1.2%

Fig. 4.2.32 - Annual temperature distribution data table for the final green house model **BEDROOM 3**. This space is within the comfort band 88.1% of the year.

| ANNUAL TEMPERATURE DISTRIBUTION | | |
|---|---|---|
| | | |
| m bed | | |
| Operation: Weekdays 00-24, Weekends 00-24. | | |
| Comfort Band: 71.4 - 83.8 F | | |
| In Comfort: 7611 Hrs (86.9%) | | |
| | | |
| TEMP. | HOURS | PERCENT |
| 53.6 | 0 | 0.00% |
| 57.2 | 0 | 0.00% |
| 60.8 | 37 | 0.40% |
| 64.4 | 282 | 3.20% |
| 68 | 675 | 7.70% |
| 71.6 | 1899 | 21.70% |
| 75.2 | 2370 | 27.10% |
| 78.8 | 2070 | 23.60% |
| 82.4 | 1272 | 14.50% |
| 86 | 155 | 1.80% |
| 89.6 | 0 | 0.00% |
| 93.2 | 0 | 0.00% |
| 96.8 | 0 | 0.00% |
| COMFORT | 7611 | 86.90% |

Temperature Range

Too Cool 11.3%

Comfort Zone 86.9%

Too Warm 1.8%

Fig. 4.2.33 - Annual temperature distribution data table for the final green house model **MASTER BEDROOM**. This space is within the comfort band 86.9% of the year.

## ***4.3 THERMAL COMFORT***

Most people are comfortable indoors if the space temperature is near 75°F and the relative humidity is near 50% (Building Science). This is considered ideal, and Hawaii's natural climate on average is very close to these numbers.

Natural ventilation relies on the wind to keep a building cool, and bring in clean fresh air. The wind will naturally ventilate a building through openings such as doors and windows depending on their orientation to the wind. In Hawaiʻi, a well-designed efficient home will take advantage of the local trade winds to help cool and keep building occupants naturally comfortable. Natural ventilation will also improve the indoor environmental air quality. We require fresh air to alleviate odors, bring in oxygen to breath and to increase the thermal comfort of the interior of the building and its occupants. For virtually all of existence, people have relied on the natural flows of their local environments, the meandering paths of rivers, the orientation of towns and buildings to the sun, and the prevailing breezes to shape their patterns of settlement. There were no air conditioners a century ago, and now people demand them. Buildings use the basic principles of fluid dynamics for cooling, warm air rises and cool air falls. The use of mechanical cooling systems can be diminished with well-sized and placed windows and proper building orientation to take advantage of the natural climate. The advantage of air conditioning for a climate like Hawaiʻi with occasional high relative humidity is that the air conditioning system can help control the humidity of the air being expelled into the space.

### 4.3a Natural Ventilation

When wind blows against a building air is forced into open windows and doors on the side of the building facing into the wind, while a natural vacuum effect pulls the air out through open windows or doors on the leeward side of the building. This is the basic principle of cross ventilation. Windows are to be placed on both the windward and leeward sides of the building so that breezes can flow unimpeded across an occupied space. Fresh air is passively brought into a building through pressure differences generated by two physical phenomena: buoyancy and wind. Buoyancy refers to the fact that a column of air differing in temperature from the air around it will either rise or fall until it reaches equilibrium.

Another method of ventilation is the stack or chimney effect, which is a common example of buoyancy. The chimney effect happens when heated air rises vertically pulling in cooler air from the outlets below. This effect helps create a vacuum which will pull more air in simultaneously (*see Fig. 4.3.1*). The chimney effect works best with high ceilings and operable windows, skylights and/or clerestory windows near the top of the space. The sizes of both the inlets and outlets have a substantial role in the amount of wind that will enter and move through a building. Landscaping around the building can also have an enhancing or diminishing effect on natural ventilation depending on the placement and size of the landscaping. Air can be guided into the building or restricted depending on the design of the landscape.

Buildings designed for natural ventilation usually have large openings and open floor plans. In a climate where the nights are considerably cooler than the days it makes sense to keep a building closed during the day to keep the heat out, and opened at night to allow the night air to help cool the building for the following day. In climates where the temperature remains similar from day to night, such as Hawai‘i, buildings should be open during the day to capture prevailing breezes to help keep the home and it's occupants cool. Weather changes frequently and even the best designs might need the assistance of mechanical heating or cooling part of the time. If executed properly and in the right conditions, passive ventilation can dramatically improve indoor air quality and thermal comfort while reducing the building's reliance on energy derived from fossil fuels, and will help the occupants connect to the outdoor environment.

For residential buildings the common ventilation rate measure is the number of times the whole interior volume of air is replaced per hour, known as air changes per hour (ACH). There is a different requirement for each room type and function. In 1989 the ASHRAE 62-2001 whole house ventilation requirements were set at 0.35 ACH, but no less than 15 cfm/person. ASHRAE's new standard 62.2-2003 requires an additional 3 cfm/100sq. ft., which increases the requirement for a 1300 sq. ft. 3 bedroom house to 0.43 ACH. Attic spaces for cooling purposes require 12-15 ACH, garages need only 4-6

ACH, indoor laundry rooms need 10-15 ACH, and kitchens require the most amount of air change rate at anywhere from 15-60 ACH. A minimum of 4 ACH is recommended for any room no matter what the function and size (Engineering ToolBox). Kitchens require the most air changes due to odors from cooking, and the heat from operating appliances such as the range, oven, refrigerator, and dishwasher which will all raise the mean radiant temperature of the space.

### 4.3b Relative Humidity

There is no “ideal” relative humidity level and temperature suitable for all building occupants. Many factors, such as personal activity and clothing, may affect personal comfort. Relative humidity creates the perception of an extremely dry or extremely damp environment. This can then play a part in the perceived temperature and thermal comfort. Acceptable relative humidity levels should range from 30% to 60% year round on a national level. In Hawaiʻi, those numbers are increased. With Hawaii’s climate and weather, humidity levels are never too low for natural comfort. Elevated relative humidity can promote the growth of mold, bacteria and dust mites, which can aggravate allergies and asthma and cause buildings to degrade over time.

In Hawaiʻi the morning hours typically have a higher relative humidity level than the afternoon and evening. On average the winter months are higher in relative humidity than the summer months. This weather pattern will actually help the natural thermal comfort of the building occupants. The highest relative humidity levels occur during the morning hours in the winter, and the lowest levels occur during the afternoons of summer. Throughout the year the average high and low relative humidity is 72% and 56%, respectively. These levels are considered to be on the higher end of occupant comfort, but not nearly as extreme or uncomfortable as other areas of the U.S.

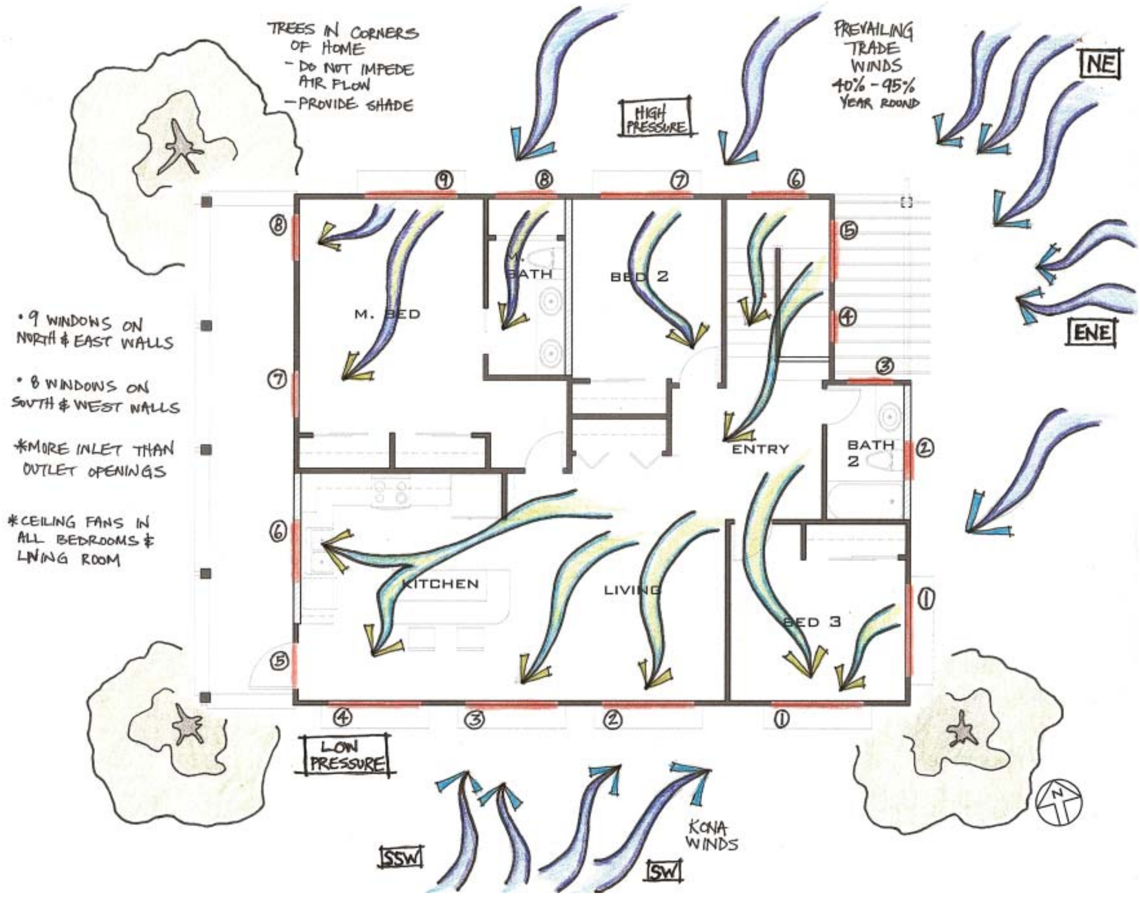



Fig. 4.3.1 - Diagram showing trade and kona wind direction in relation to plan type one. This diagram also illustrates the number and placement of windows for cross ventilation purposes.

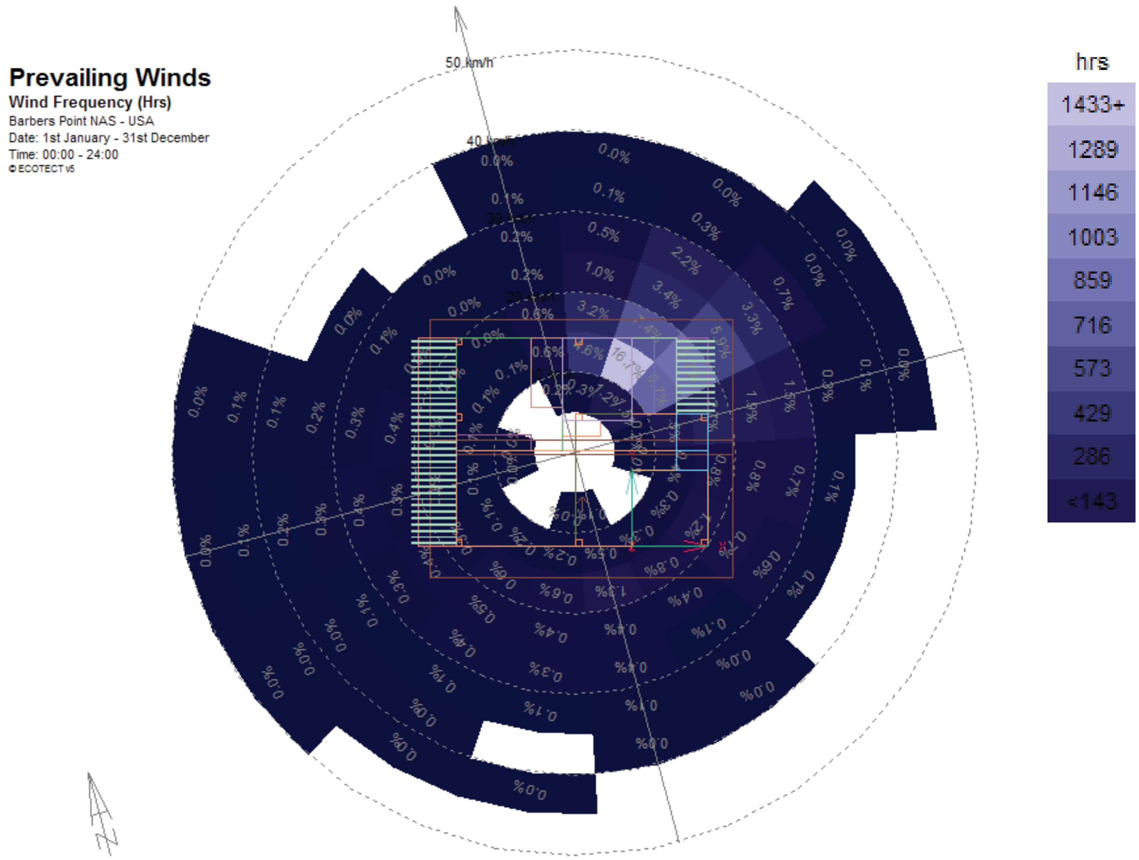



Fig. 4.3.2 - Image shows the prevailing winds throughout the year with plan type one displayed over the graph. The trade winds blow out of the north-west the majority of the year at an average rate of 2.9 to 4.2 m/s. The wind rarely comes from the east or south due to the direction of the trade and kona winds in Hawaii.

## 4.3c Ecotect Natural Ventilation and CFD Analysis

The results for the three Ecotect models for interior temperatures do not take into account the perceived cooling effects of natural ventilation. Providing natural ventilation within the spaces of the home will help the occupants feel the temperatures are closer to within the comfort band. Using wind data collected from the USDOE, the base case model and final green house model are tested and analyzed for interior flow rates and patterns based on monthly averages and maximum wind speed rates. The wind data has been collected from the past 30 years for Barbers Point, Oahu, about 5 miles from the project site. The average monthly wind speed ranges from a low of 2.9 m/s in July to a high of 4.2 m/s in May. The maximum monthly wind speeds range from a low of 8.2 m/s (June – September) to a high of 12.4 m/s in January. The trade winds come from the north-east 55.5% of the year and from the east 19.6% of the year. Kona winds blowing from the south and south-west direction only occur 8.3% of the year, which is enough to test and design the homes for when this occurs (US Department of Energy).

The base case model and the final green house model are tested for both trade winds blowing out of the north-west at the monthly high rate of 4.2 m/s, and kona winds blowing out of the south south-west direction at a rate of 4.2 m/s (*see Figs. 4.3.3 – 4.3.10*). In addition the final green house model is analyzed for trade winds for the monthly low rate of 2.9 m/s, and the maximum gust speed of 12.4 m/s (*see Figs. 4.3.11 – 4.3.14*).

Interior wind speed plays an important role in natural thermal comfort. Due to people's diverse definition of comfort, there is no specific rate that creates interior comfort. Wind movement is barely noticeable at speeds under 0.4 m/s, hair and papers will start to move at about 0.8 m/s and around 3.0 m/s it starts to feel gusty (Ecotect Community Wiki). This project aims to provide wind speeds of at least 1.5 m/s throughout the main occupied spaces of the homes. If the homes can achieve wind speeds of at least 1.5 m/s then the occupants can control the air movement based on their comfort preferences through the operable windows. For the times of the year that there is zero air movement, ceiling fans have been installed in all bedrooms and the living area to provide some air movement.

The analysis shows that the final green house does achieve levels of over 1.5 m/s in the highly used spaces when the wind speed is 4.2 m/s or higher for both trade and kona wind conditions.  When the wind speed is 2.9 m/s, the low monthly average, the majority of the house receives less than 1.5 m/s.  The house still receives air movement through each space, but at an average of about 0.5 m/s, which still provides good air movement during the worst case scenario based on monthly averages.  The analysis for the highest wind speeds for the year, 12.4 m/s, shows that the interior wind speeds are well above 1.5 m/s.  The interior wind speeds can reach over 6.0 m/s during these times, at which point windows will have to be closed to keep papers and belongings in place.

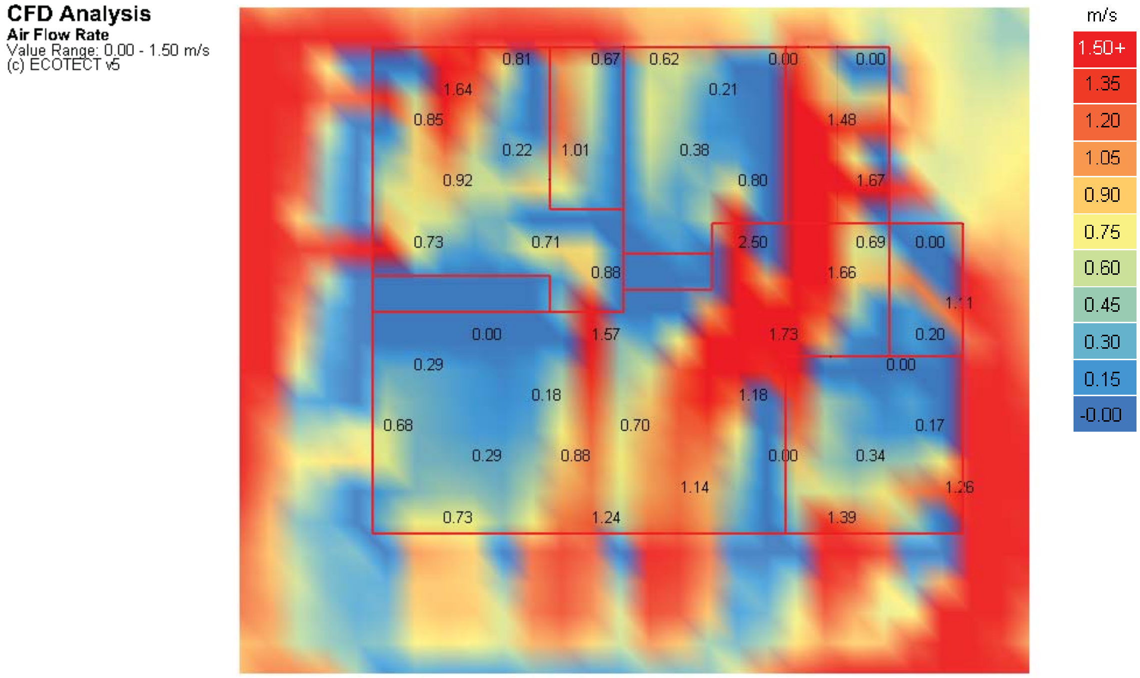



Fig. 4.3.3 - Plan view showing air flow rates throughout the interior of the final green house model. The values are expressed as wind speed in meters per second (m/s). The values range from a low (blue) of 0 m/s to a high (red) of 1.5+ m/s. This image shows the rates based on **trade winds** blowing at 4.2 m/s from the north-east.

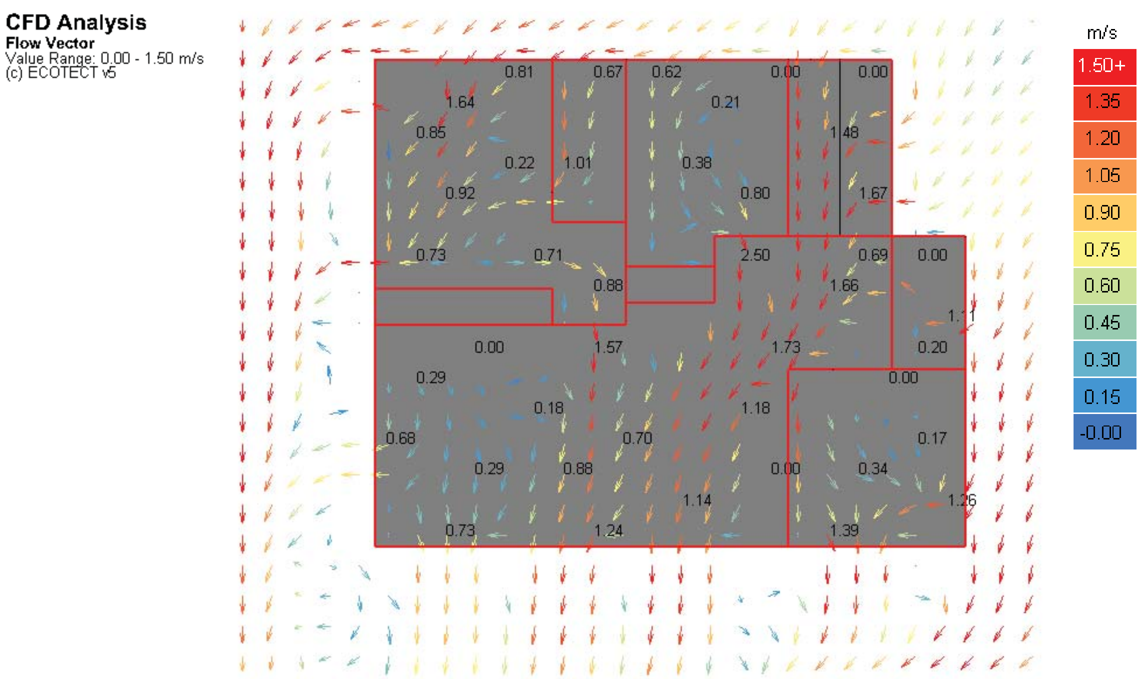



Fig. 4.3.4 - Plan view showing the air flow patterns throughout the interior of the final green house model based on **trade winds** blowing at 4.2 m/s from the north-east.

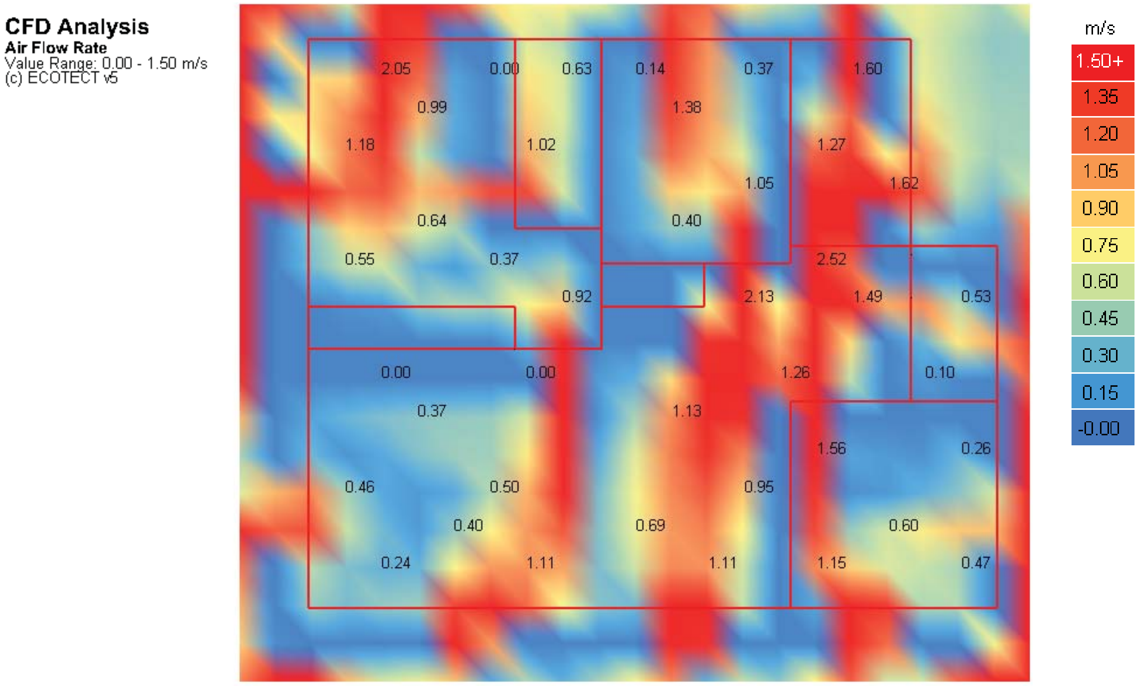



Fig. 4.3.5 - Plan view showing air flow rates throughout the interior of the base case house model. The values range from a low (blue) of 0 m/s to a high (red) of 1.5+ m/s.  This image shows the rates based on **trade winds** blowing at 4.2 m/s from the north-east.

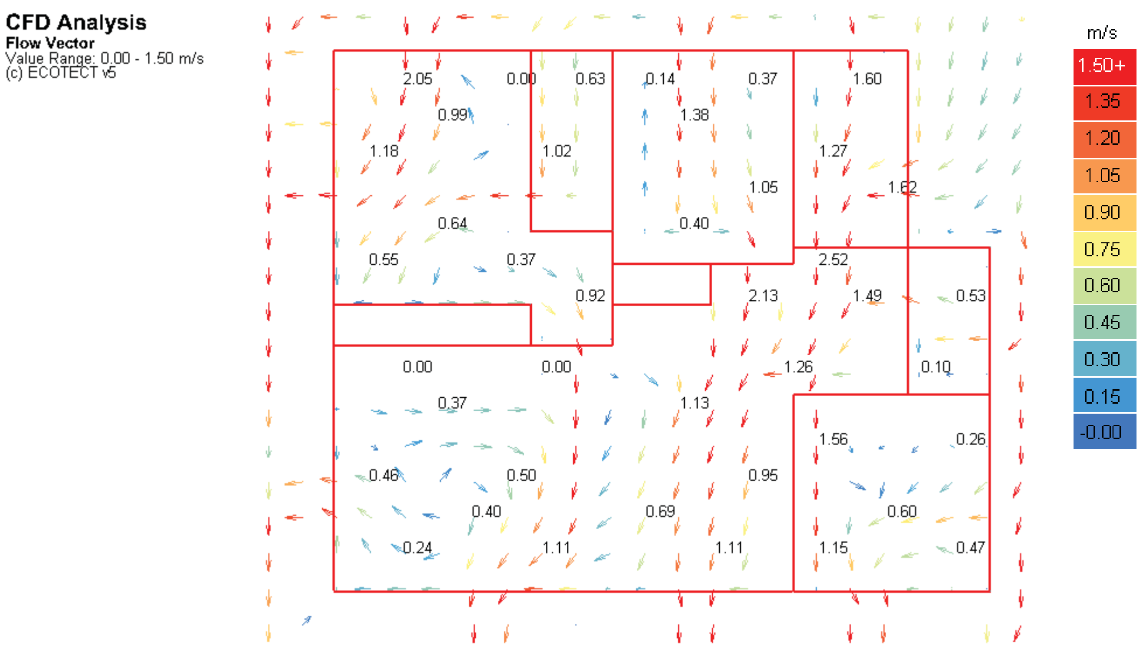



Fig. 4.3.6 - Plan view showing the air flow patterns throughout the interior of the base case house model based on **trade winds** blowing at 4.2 m/s from the north-east.

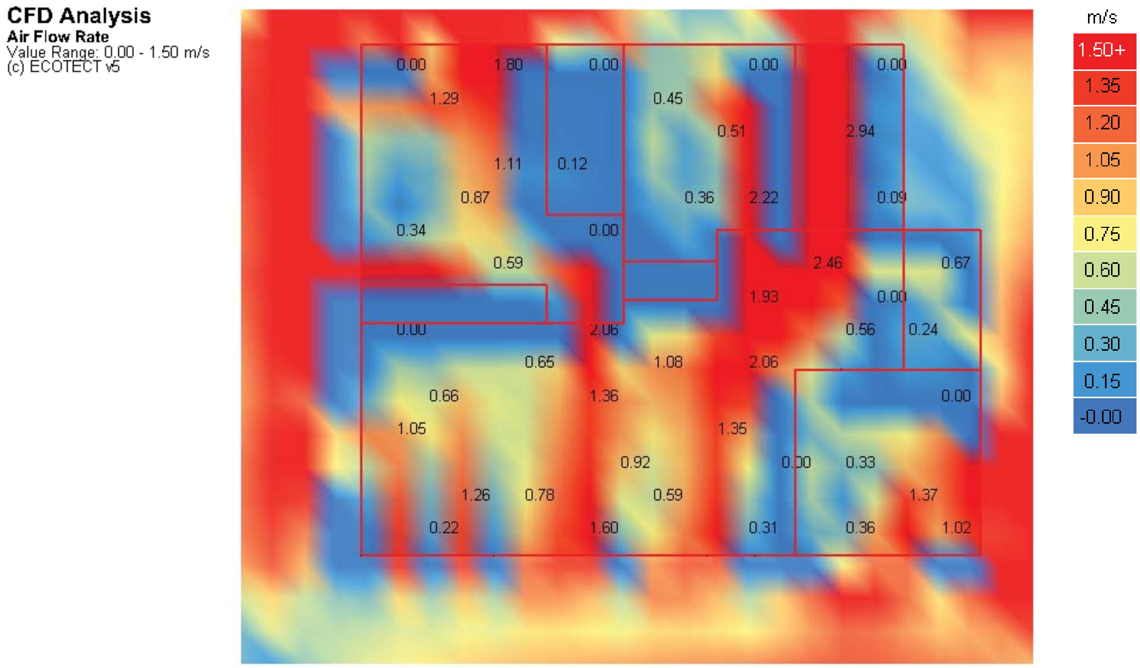



Fig. 4.3.7 - Plan view showing air flow rates throughout the interior of the final green house model. The values range from a low (blue) of 0 m/s to a high (red) of 1.5+ m/s. This image shows the rates based on **kona winds** blowing at 4.2 m/s from the south south-west.

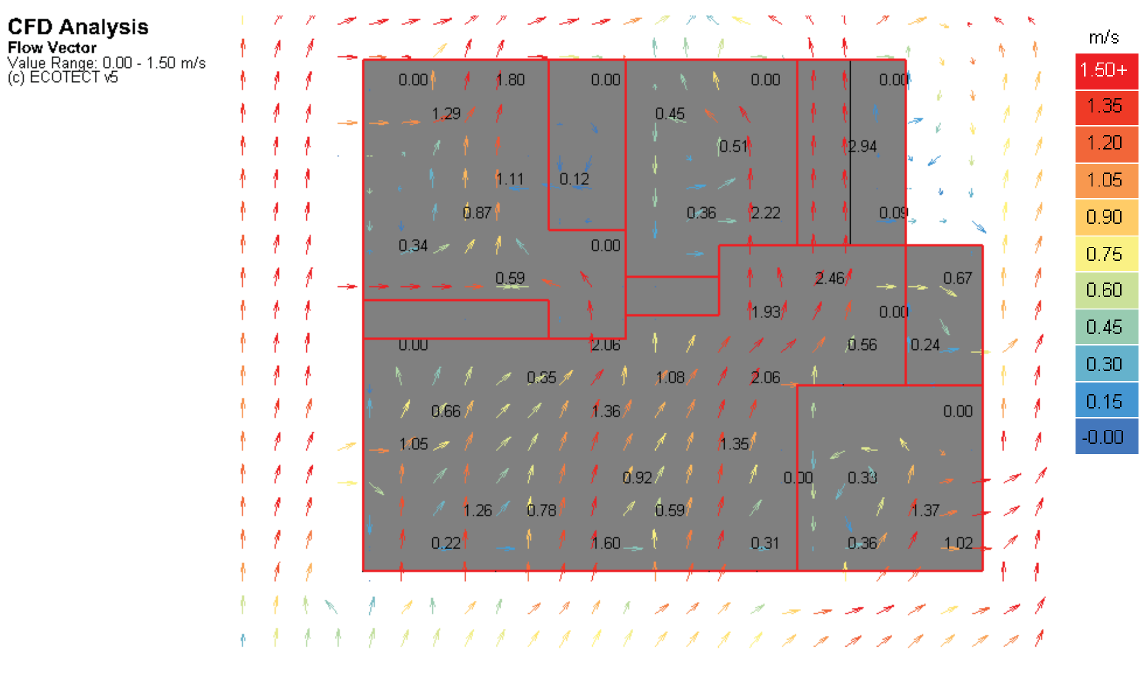



Fig. 4.3.8 - Plan view showing the air flow patterns throughout the interior of the final green house model based on **kona winds** blowing at 4.2 m/s from the south south-west.

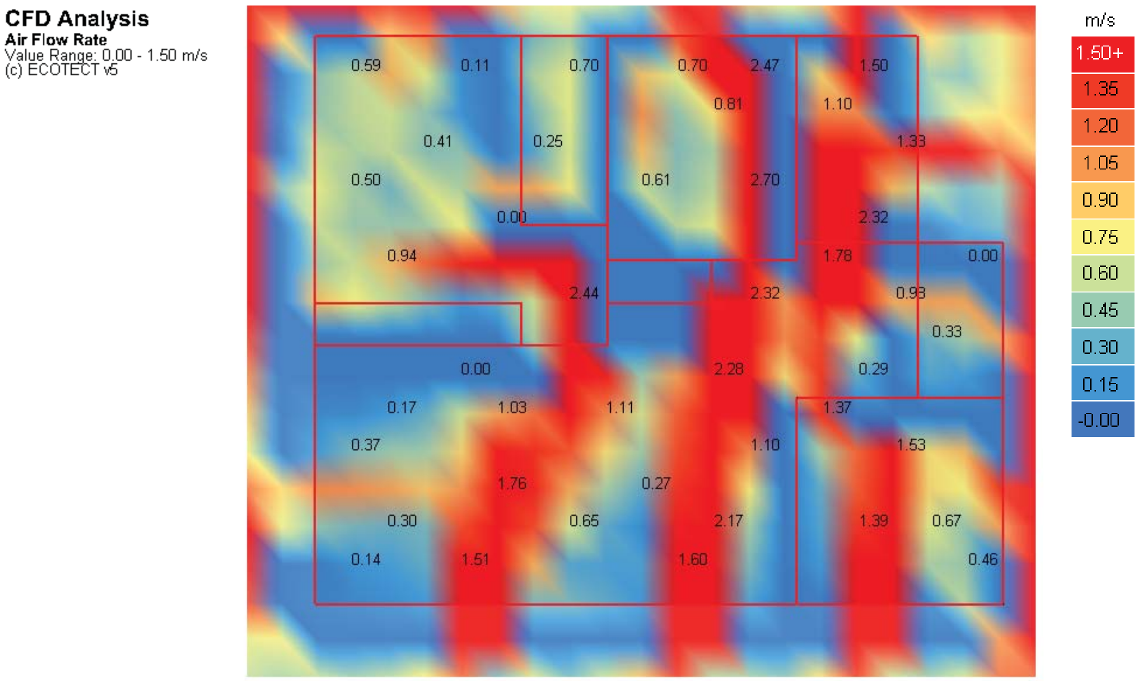



Fig. 4.3.9 - Plan view showing air flow rates throughout the interior of the base case house model. The values range from a low (blue) of 0 m/s to a high (red) of 1.5+ m/s. This image shows the rates based on **kona winds** blowing at 4.2 m/s from the south south-west.

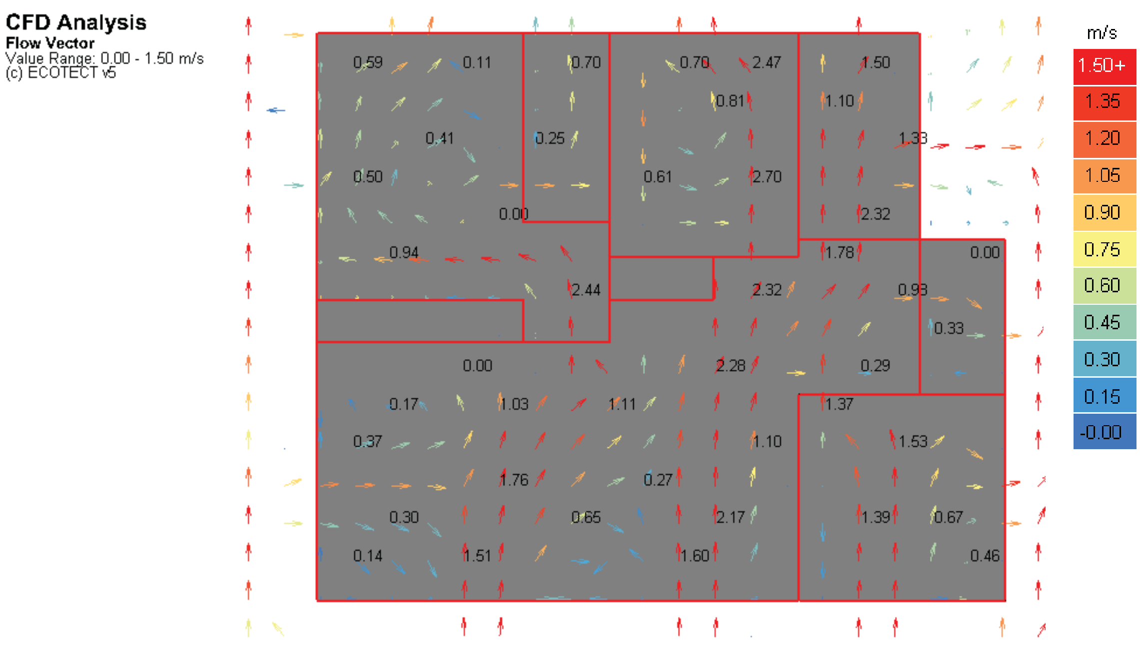



Fig. 4.3.10 - Plan view showing the air flow patterns throughout the interior of the base case house model based on **kona winds** blowing at 4.2 m/s from the south south-west.

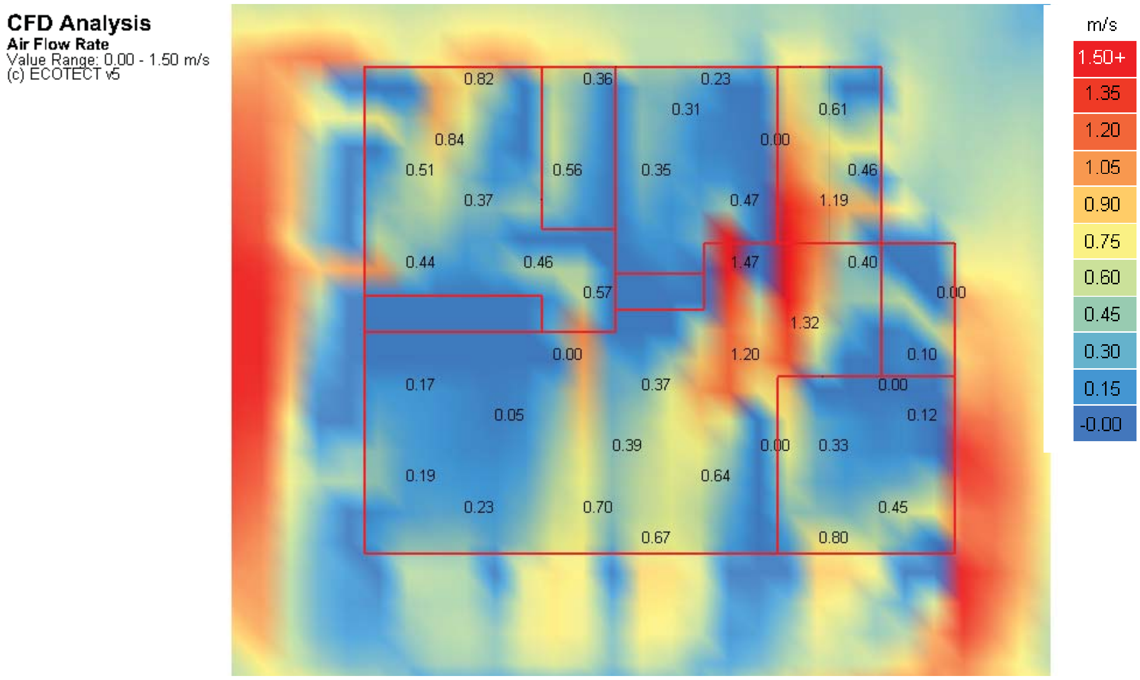



Fig. 4.3.11 - Plan view showing air flow rates throughout the interior of the final green house model. The values range from a low (blue) of 0 m/s to a high (red) of 1.5+ m/s. This image shows the rates based on **trade winds** blowing at 2.9 m/s from the north-east.

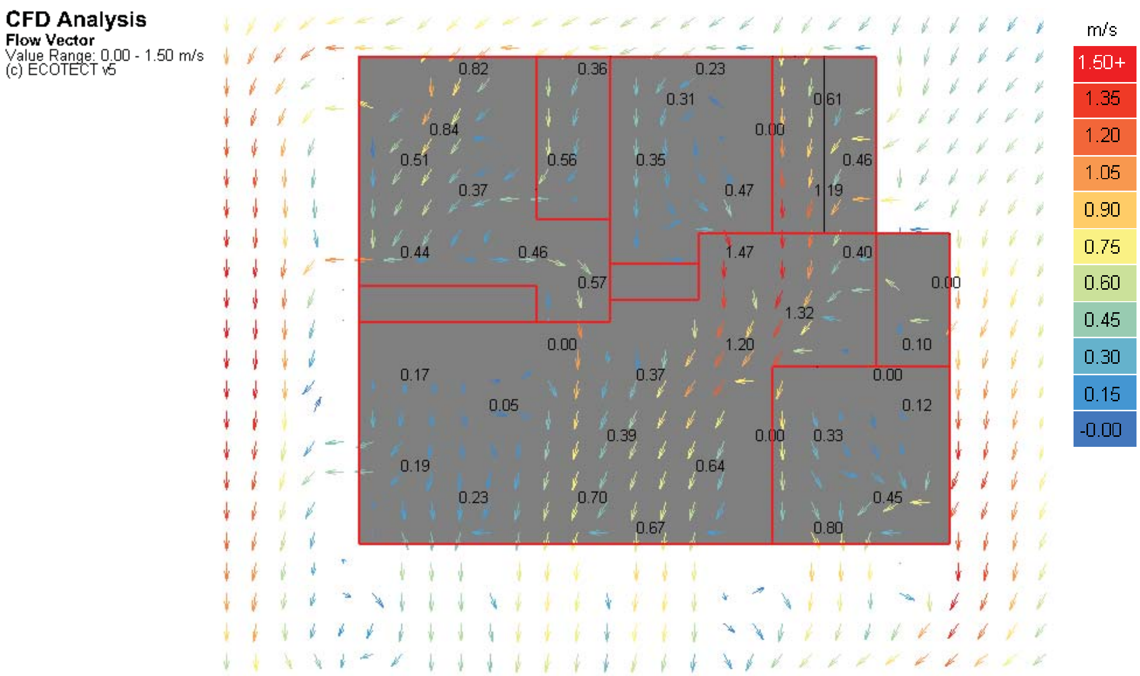



Fig. 4.3.12 - Plan view showing the air flow patterns throughout the interior of the final green house model based on **trade winds** blowing at 2.9 m/s from the north-east.

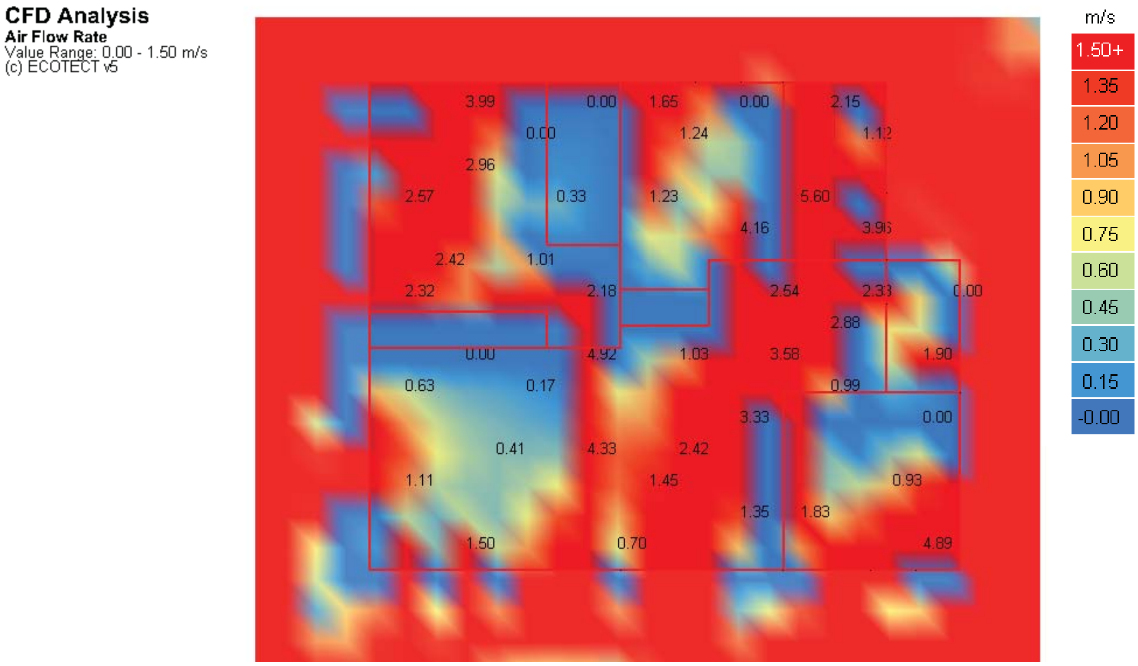



Fig. 4.3.13 - Plan view showing air flow rates throughout the interior of the final green house model. The values range from a low (blue) of 0 m/s to a high (red) of 1.5+ m/s. This image shows the rates based on **trade winds** blowing at 12.4 m/s from the north-east.

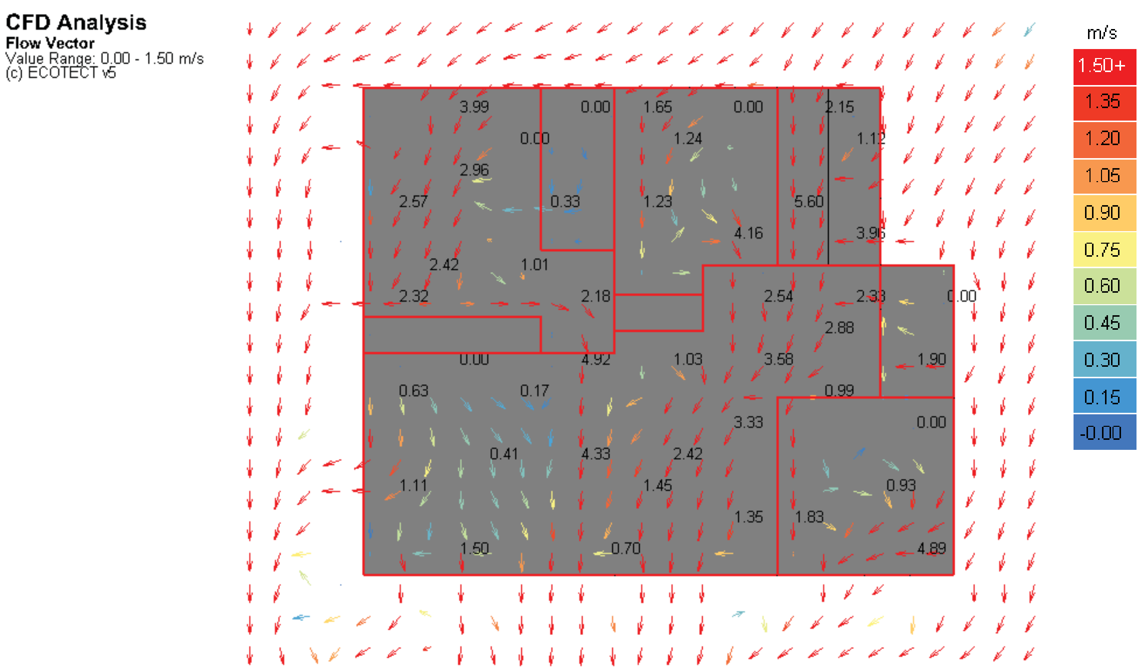



Fig. 4.3.14 - Plan view showing the air flow patterns throughout the interior of the final green house model based on **trade winds** blowing at 12.4 m/s from the north-east.

## *4.4 WINDOWS AND GLAZING*

Windows provide us with daylight, ventilation and views to the natural world. Glass or glazing has many different functions including sunlight control, heat gains and losses, condensation control, acoustic control, security issues, color effects, energy requirements, and daylight performance. However, windows are still one of the least understood components of building design. A well designed building maximizes the use of natural light without compromising energy efficiency. There have been many advancements in window types and glazing properties in the recent years. Window design has improved dramatically in the last 20 years; high performance windows can now equal or exceed the performance of even an insulated wall. Consequently, the strategy of reducing window area to reduce energy use is no longer as significant if highly efficient windows are used. The total glazing area of a building has a significant negative impact on the heating and cooling energy use when using poorly insulated single glazed windows. Windows transmit not only light, but also solar heat through the building envelope. Single pane clear glass is 30 times more vulnerable to heat gain from sunlight than an opaque wall. Shading the glass will reduce the heat impact by up to 1/3, although that is still 10 times more vulnerable than an opaque wall, making them a source of major solar heat gains (Sensible House). However, if we choose the proper high efficiency windows for the climate, we can increase overall window area without reducing the energy efficiency of the building.

### 4.4a Window Rating System

A window's performance is measured and rated based on its U-factor, its solar heat gain coefficient (SHGC), its visible transmittance (VT), the air leakage rate (AL), and its light-to-solar gain (LSG) factor. The National Fenestration Rating Council (NFRC) is a non-profit public/private organization which tests, certifies and labels windows, doors and skylights based on the energy performance rating of its U-factor, SHGC, VT, AL, and condensation resistance (CR). The NFRC has developed a window energy rating system based on whole product performance, which includes the window and the window frame.  The NFRC label appears on all doors, windows and skylights which meet the NFRC standards and are part of the ENERGY STAR program. The NFRC designates which products are optimal for each state and climate zone.  While there are some windows which are only ENERGY STAR certified in specific states due to the climate zone, there are also windows which qualify as energy efficient in all 50 states.  They guarantee high energy performance and thermal comfort for all regions and all seasons.

The U-factor is the rate at which a window, door or skylight conducts non-solar heat flow.  It rates how much heat is being lost or gained due to temperature differences from the interior to the exterior through the window, door or skylight.  In the United States, the U-factor is usually expressed in BTU's per square foot per hour ($BTU/ft^2/hr$); the SI equivalent is $W/m^2$-K.  The lower U-factor provides more insulating value, and the lower the value, the more energy efficient the window, door or skylight.  The insulating value is indicated by the R-value, which is the inverse of the U-factor.  To achieve the energy efficient standard, the glass is coated with a thin layer of material that is engineered to transmit or reject certain frequencies of radiation.  This glass is known as low-emissivity (Low-E) glass.  A low U-Factor is important in passive cooling design, but the value is less important than the SHGC value in warm climates like Hawai‘i.

The SHGC is the fraction of solar radiation admitted through a window, door or skylight.  The radiation is transmitted directly through the window, and absorbed and released as heat inside the building.  A window with a high SHGC rating is more effective at collecting solar heat gain during the winter.  A window with a low SHGC is more effective at reducing the solar heat gain by reflecting the heat from the sun away from the building.  An SHGC value of 0.40 means that 40% of the solar radiation passes into the building, and the remaining 60% is both absorbed by the window, and reflected back into the environment.  It is typical that a window that has a low U-value will also reject most solar heat gains, meaning it also has a low SHGC.  A low SHGC value is the most important window property in warm climates.

The VT is the amount of light that is transmitted through the glazing of the window, door or skylight.  A product with a higher VT transmits more light.  If a window transmits less than 70% of visible light, indoor plants can start to die or have a slower growth rate. While VT theoretically varies between 0 and 1, most values are between 0.3 and 0.8. A high VT is desirable to maximize daylight and view, no matter what the climate. The LSG is the ratio between the SHGC and the VT. It gauges the efficiency of the window, door or skylight to transmit light while blocking out solar heat. The higher the number, the more visible light transmitted while blocking unwanted heat (Efficient Windows). The NFRC label does not include the LSG; however, it is useful in determining which windows to use for a specific climate. The two most important factors of the windows performance are the U-Factor and the SHGC (*see Figs. 4.4.1 and 4.4.2*). Using the correct window type and proper shading techniques will make a drastic difference in lowering energy bills due to cooling needs.

The Efficient Windows Collaborative has tested and recommended window, skylight and door properties based on the climate zones for all 50 states. In Hawai‘i, it is recommended that windows have a U-Factor lower than 0.60. This number is different for skylights, in which the U-Factor should be lower than 0.70. The SHGC should be lower than 0.27 for windows and less than 0.30 for skylights (Efficient Windows). The optimum window type for the Hawai‘i climate based on the NFRC ratings is a double glazed window with low solar gain Low-E coating, and filled with either argon or krypton gas. An example of this type of window is the Pella 11/16” Vent Unit Sun Defense Low-E 1G with Argon with 3mm glass. This window provides a U-Factor of 0.29, a SHGC of 0.21 and a VT of 47%. Single glazed clear glass with an aluminum frame provides a U-Factor of 1.16, an SHGC of 0.76 and a VT of 0.75. The only characteristic of the clear glass that is more advantageous is the amount of visible transmittance, which is one and a half times greater than the aforementioned optimum window type for Hawai‘i. Wood, wood clad and vinyl frames are better at insulating than aluminum frames, and will assist with the rating of the window’s energy efficiency. Aluminum is an excellent conductor of heat and therefore not a good choice of material for window frames in the Hawaiian climate. According to the Pella Windows website, of all the glazing that is rated for the southern zone of the US, the highest VT is 53%. This number is well below the recommended VT, but it is more important to pick a window with a low U-Factor and SHGC. Pella has glazing with properties as low as a U-Factor of 0.26, and a SHGC of 0.17, but it only has a VT of 36%.

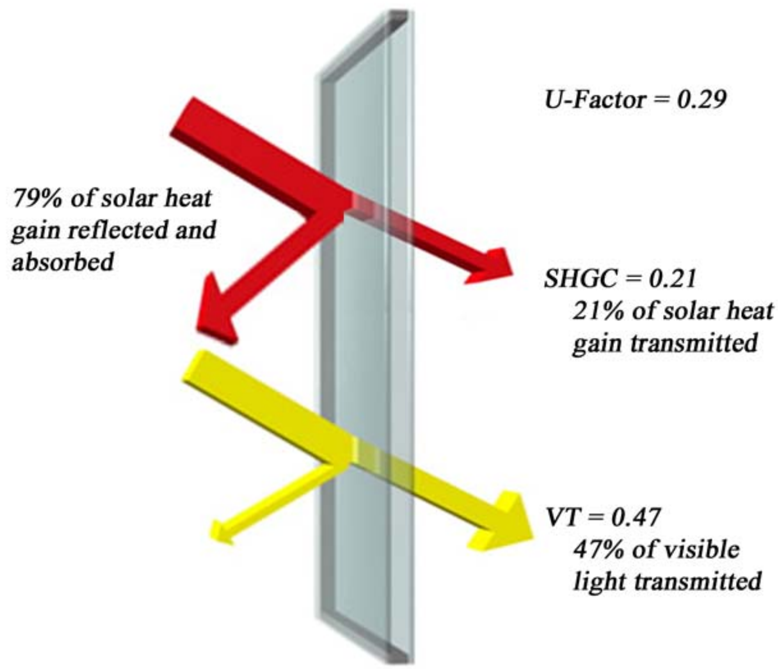



Fig. 4.4.1  Diagram showing the properties of spectrally selective glazing
*Source: www.efficientwindows.org*

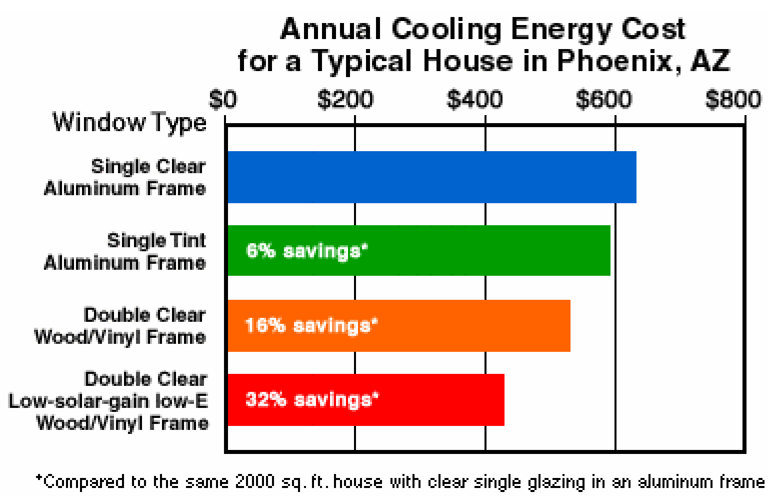



Fig. 4.4.2  Chart showing the effects of various glazing types and cooling costs for Phoenix, Arizona, which has a similar cooling climate to Hawaii
*Source: www.efficientwindows.org*

### 4.4b Window Coatings

Low-emissivity (Low-E) coatings on glazing control the heat transfer through windows with insulated glazing. Low-E coatings are microscopically thin, virtually invisible metal or metallic oxide layers deposited on a window or skylight glazing surface primarily to reduce the U-factor by suppressing radiative heat flow. The type of Low-E glass that is preferable in Hawaiʻi is sometimes called spectrally selective glass. Spectrally selective coatings are tinted glazing with optical properties that are transparent to certain wavelengths of energy and reflective to others. Typical spectrally selective coatings are transparent to visible light and reflect short-wave and long-wave infrared radiation. There are different types of Low-E coatings which have been designed to allow for high solar gain, moderate solar gain or low solar gain. A Low-E coating typically also lowers the visible transmittance of a window unless specifically designed to allow a higher transmittance. To keep the sun's heat from transmitting to the interior for hot-humid climates, the Low-E coating should be applied to the outside pane of glass. Low-E coatings typically cost as much as 10-15% more up front than typical windows, but they may reduce the energy loss by as much as 50% overall (US Department of Energy). Unfortunately, most building owners and developers tend to look more at the initial costs of construction rather than the overall savings over the life of the building.

Most Low-E coatings are generally applied during manufacturing of the glass however there are some available to do yourself on existing windows. For existing homes, you can purchase the inexpensive film and apply it to your existing windows without having to replace the windows. They also reduce glare and solar-heat loss or buildup, add privacy, lower energy bills, and even add resistance to shattering. One of the few disadvantages of adding an aftermarket film to a window is that it might affect the windows original warranty.

## *4.5 SHADING TECHNIQUES*

In 1980, about 27% of all American homes had central air conditioning. By 2001 that figure rose to about 55%. Air conditioners were installed in 77% of new homes built in 1988, and Americans were spending billions of dollars a year to operate them (US Energy Information Administration). A carefully and appropriately designed house can save up to 66% of annual electricity costs. In the pre-refrigeration days architects had the responsibility to orient buildings properly and design for its shading. There are now newer technologies and timeless building design guidelines which may help lower a building's energy expenses by shading a building to prevent heat from entering the interior. There are many ways to shade a building from the sun and its radiant heat. Direct solar radiation must be blocked by a roof overhang or other devices such as awnings, shutters or trellises. Other sources of shading for a building are landscaping, shade screens and interior shades such as curtains, blinds or roller shades.

### 4.5a Landscaping

Trees offer excellent natural shading and cooling. Big, leafy trees in particular will help shade the building more effectively and for a longer duration than smaller or thinner trees. Trees also help shade driveways, sidewalks and patios, which can absorb and reflect unwanted sunlight and heat into a building. In order to keep themselves cool, trees pump water up from the ground into their leaves, and as this water evaporates from the surface of the leaves, it cools the tree. This "evaporative cooling" also cools the surrounding area near buildings, therefore the more natural vegetation the cooler the surrounding air. In contrast to this, as elements such as concrete patios and driveways receive sunlight they absorb the heat and create the heat island effect. The heat island effect causes an unwanted rise in ambient exterior temperatures. The less heat absorbing elements near buildings the cooler the air will be. Using trees as shading devices will work best when the tree is within 5 to 20 feet of the building, depending on the size and shape of the tree. The farther from the building, the taller the tree needs to be to effectively shade and cool the building. Deciduous trees are best for south yards in most of the US, because their canopies are broad and dense, and they lose their leaves in winter to allow sunlight to enter the house during the cool winter months. Evergreens don't lose their leaves in the winter and can work well in cooling climates where shade is required for most of the year. Landscaping can be designed to be a pleasing architectural expression on the exterior of the building. It can also be a way of directing or redirecting airflow providing cleaner, fresher air around the building. Shade trees should be of a high branching type to allow the prevailing breezes to pass under the canopy and into the building. Large bushes or small trees should be kept away from the building or designed so that they do not block the natural breezes.

### 4.5b Trellises

Adding trellises is a great way to bring diffused, broken light into the building. Trellises are permanent structures, often made of wood, which partially shade the building. Allowing vines to grow over the trellis allows for increased shading and evaporative cooling. The advantage of using vines on trellises is that they usually grow much more quickly and provide shade and energy savings quickly, rather than waiting for trees to grow to full size. They also provide a unique design approach that is attractive, flexible and constantly changing. In addition to the shading advantages of trellises, they can be designed as architectural features and provide an interesting play of shadows.

### 4.5c Overhangs and Awnings

The most effective way to completely block out unwanted sunlight is to use the roof as an overhang or attach an awning to the building. The size of the overhang is very important and will vary depending on the building location. Shading a building should be the first line of defense against excessive heat gain. There are many variables when considering the size of the overhang: latitude, climate, solar radiation transmittance, illuminance levels, and window size and type. Overhangs and awnings are most effective on the south side of the building, which receives the most amount of sunlight throughout the day and year. Roof overhangs will not provide effective shading to the east or west facing walls due to the low sun angle during the morning and afternoon. Short overhangs are required to block the sunlight on the north facing walls in Hawaiʻi. Correctly designed overhangs, on each side of the building, will also help stop rain from reaching the structure and causing deterioration. Overhangs are generally permanent fixtures on buildings so they have to be designed precisely for the building, the local climate and building orientation. Awnings are similar to roof overhangs and shade a building in the same way. They are elements attached to the building and can be permanent or temporary. Some designs implement operable awnings which can be rolled out when necessary, or tucked away when not needed.

### 4.5d Shade Screens

Shade screens are screens which are attached to the exterior of a window. They are usually made of wood, aluminum or plastic/vinyl. The screens are only necessary on windows which get direct sunlight. Shade screens can block as much as 100% of sunlight, depending on style and material. There are many styles and designs of shade screens for various effects. There are vertical shade screens, horizontal shade screens, operable screens, and crated shade screens which combine vertical and horizontal screening. Operable screens have either movable parts to allow more or less light through the window, or the whole system can move to completely shade or completely open a window to sunlight.

In addition to exterior shading devices there is a large variety of interior shading options. These options include: blinds, shutters, shades, panels and curtains. Interior shading provides the user the freedom to allow sunlight to enter the interior or block it completely. The disadvantage to interior shading products is that they do not stop heat from entering the building; they can only control the sunlight the interior receives. A combination of both exterior and interior shading maximizes heat reduction and controllability. It is important to utilize interior shading devices on the east and west facing windows due to more direct sunlight on those sides of the building. Shading devices such as overhangs and light shelves cannot completely shade the windows on the east and west facing walls throughout the day and year.

# ***CHAPTER 5 ENERGY EFFICIENCY STRATEGIES***

## ***5.1 DAYLIGHTING***

Daylight is free; it is the most energy efficient source of illumination. In the days before the invention of electric light, the use of daylighting strategies was a necessity for architects. Sunlight creates a feeling of warmth and comfort that is unmatched by any type of electrical lighting, and can introduce life, variation and drama into otherwise banal spaces. One of the biggest advantages of proper daylighting strategies is the displacement of daytime electric lighting, which will save on electric energy costs. Electric lighting directly accounts for 20% to 25% of the total electricity used in the United States and 37% of the total electric lighting load comes from commercial buildings. The percentage of energy use from electric lighting in homes with HVAC systems is about 12%, and the percentage in homes without mechanical conditioning goes up to about 22% (ENERGY STAR). These numbers can be greatly reduced by well thought-out daylighting strategies. There is a positive correlation between daylighting and academic performance, employee performance and human comfort within buildings. A study by the Herschong Mahone Group concluded that students performed up to 20% better in reading and math in classrooms with well designed diffused daylighting than students in artificially lit classrooms. Buildings with great daylighting design have fewer problems relating to the well-being and health of the occupants.

### 5.1a Direct Daylight and Diffused Daylight

There are two basic types of daylight that can be used within buildings: direct daylight and diffused daylight. A great definition of direct daylight is from the book Lighting: Good Ideas by Marta Feduchi: "Direct daylight is an intense source of sunlight that reaches the interior of a home [building] through windows or other openings. The illuminated colors stand out while some nuances disappear in the shadows, creating volumes, shadows and textures that change throughout the day". The other type of light, diffused daylight, also called indirect daylight, is the light that is filtered through clouds, blinds, curtains, landscaping, pollution, mist or the atmosphere. Indirect daylight is also defined as light that is reflected into a space from light shelves, ceilings or walls, exterior surfaces, light pavement or grass (*see Figs. 5.1.1 – 5.1.2*).

In Hawaiʻi it is advantageous to keep the direct sunlight entering the building to a minimum, while still maintaining sufficient daylight levels for the interior. This strategy is accomplished through shading windows with extended roof overhangs, wood screens and landscaping, as well as providing indirect lighting through the use of shade/light shelves on most of the windows. With enough daylight entering the building electric lighting can be completely obviated during the daytime. However, during the hottest part of the day direct sunlight can create a significant increase in the interior ambient temperature of the building.

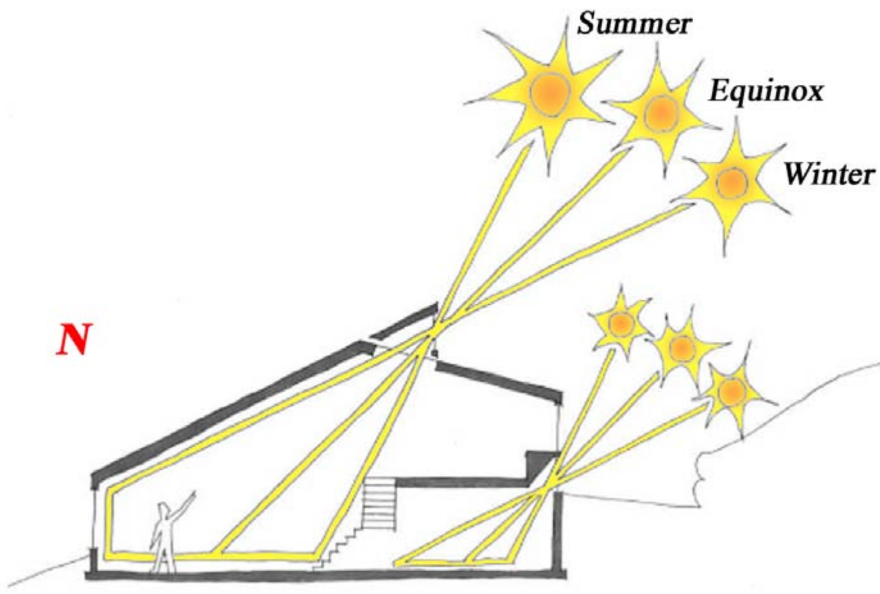



Fig. 5.1.1 Sunlight Entering the Building at different Seasonal Angles
*Source: www.solarns.ca*

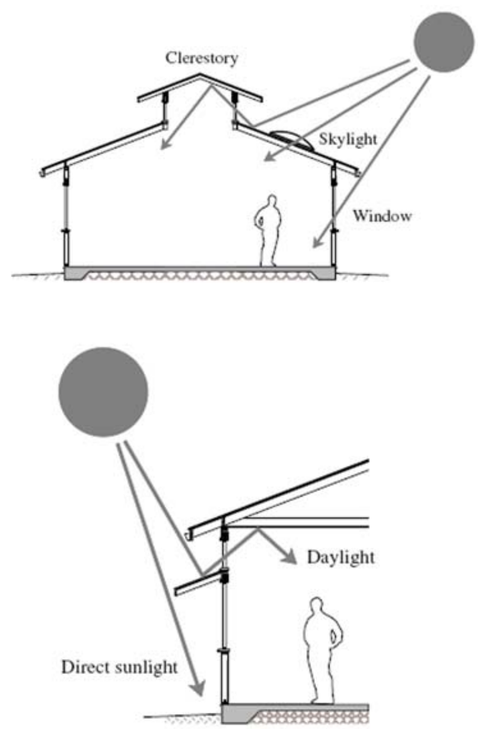



Fig. 5.1.2 Direct and indirect sunlight entering a building
*Source: Field Guide for Energy Performance, State of Hawaii*

5.1b Sunlight and Daylight

The sun provides us with two benefits of which building design should take full advantage of; it provides us with heat and light, essentially sunlight and daylight. No matter where we live in the world, we will all want to take advantage of daylight during the day to minimize the use of electric lighting. It is a universal energy savings technique. However, depending on the climate zone the building is located in, different levels of sunlight for heat during the day are necessary. The United States is broken up into three different climatic zones: the northern, central and southern zones. The northern zone is mostly a heating climate throughout the year, the central zone has both a heating climate in the winter and a cooling climate in the summer, and the southern zone is mostly a cooling climate. For a house in Hawaiʻi, which lies in the southern zone, we will want to block the direct sunlight during the day to keep the building cool, but will still want to bring in sufficient daylight to help alleviate the use of electric lights. A well designed home maximizes the use of daylighting without compromising energy efficiency. It is best to consider the size, location and primary function of the window. Will the window frame a view, capture prevailing breezes, allow adequate light or provide an architectural balance?

Daylighting is free, provides a more natural, pleasant light source, and will save the building owner money when designed for and used properly. The two most common types of electric bulbs are incandescent and fluorescent, and the electricity used by each and the Lumens of light produced varies. The Florida Solar Energy Center states that "to deliver 1000 Lumens per square meter, incandescent lighting requires 133 watts per meter squared ($W/m^2$) of illuminated area, fluorescent lighting requires 26.67 $W/m^2$, and daylighting requires 2.78 $W/m^2$". The 2.78 $W/m^2$ is not energy used by daylighting, but from the required energy used by an air conditioner to remove the heat associated with the daylight. This results in a direct correlation to energy costs when comparing the electric lighting to daylighting. The ratio of electric incandescent lighting to daylighting is 48 to 1, and the ratio for fluorescent lighting to daylighting is 9.6 to 1. From this we can see that incandescent lighting is much more demanding of electric energy and thus electric costs will be higher than with either fluorescent lighting or daylighting.

The savings associated with daylighting do not happen all day every day, unfortunately. It is important to take advantage of the daylight during the day when available to help offset the cost to light the home at night and during cloudy times. There will be times when daylighting levels do not meet the room footcandle (fc) requirements, and supplemental electric lighting is necessary. A footcandle is defined as the illumination on a surface one square foot in area on which there is a uniformly distributed flux of one Lumen. Footcandles are measured by the total Lumens (lm) divided by the area in square feet. Different rooms and specific purposes require different levels of lighting measured in footcandles, or Lux, which is the SI unit (1Lux = 10.47 fc). More footcandles are required for more detailed and specific tasks such as precision drawing or model making. The footcandle levels required in homes are relatively low compared to commercial requirements. Dining rooms require between 10-20 fc, kitchens require a level of 50-75 fc, reading requires 20-50 fc, areas that have the need for sufficient lighting for extreme detail to build models, for example, require 100-200 fc, and the required level for entertaining, relaxing, entries and hallways can be as low as 5-10 fc (Guth). Lighting levels required in a residential home can easily be achieved purely by daylight and alleviate the need for electric lighting until nightfall. Daylighting is generally the single most effective energy saving strategy used in energy efficient buildings.

The total amount of daylight available in Hawai‘i is a great advantage for daylighting purposes (*see Figs. 5.1.3 and 5.1.4*). The actual sunshine hours account for 71% of possible hours from sunrise to sunset for the yearly average with the other 39% being cloudy sky conditions. The minimum amount of sunshine is in the winter during the months of December and January with an average of 64%. The sunniest months of the year in Hawai‘i are August and September, with monthly averages of 78%. There are periods of complete cloud cover, and range from a high of 34% of the time in the winter to a low of 18% in the summer. Due to the tropical weather patterns and high amount of wind, partly cloudy conditions occur during the majority of the year, ranging from a high of 80% to a low of 71% (City Data).

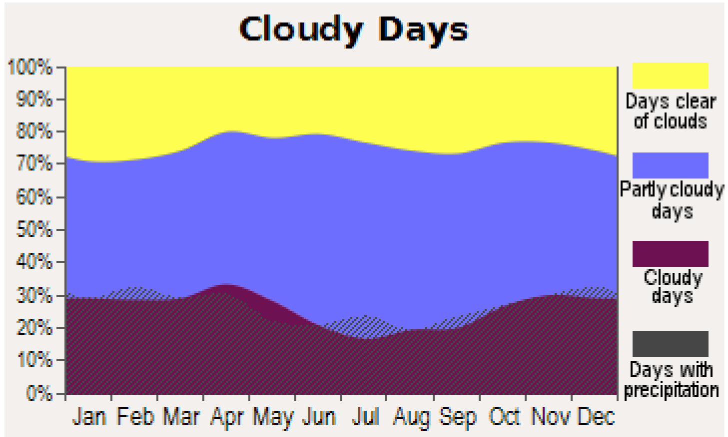



Fig. 5.1.3  Average cloudy days for Honolulu
*Source: www.city-data.com*

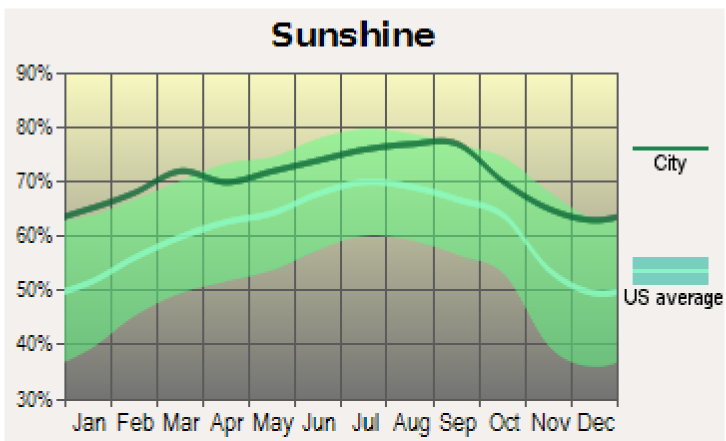



Fig. 5.1.4  Average sunshine percentage for Honolulu
*Source: www.city-data.com*

## 5.1c Window Types

Daylight can enter a building in many ways. Buildings can bring light into the interior through windows, clerestories, skylights, light tubes, roof monitors and atriums. Side lighting is categorized as vertical windows or clerestories. Clerestories are windows high up on a wall, usually just below the roof and above eye level. Window placement and size will vary depending on the climate zone where the building is located. A general rule of thumb is that there should be more than enough daylight in a building with 15% or less window-to-wall area. Top lighting includes skylights, atriums and roof monitors and will allow the most amount of daylight and sunlight to penetrate into the interior space. Skylights are windows installed on the roof thus they bring in light from above. The advantage to skylights is they provide a lot of daylight, but also allow unwanted heat gain into the space due to the difficulty in shading the skylights. The size of a skylight should never be more than 5% of the floor area in rooms with many windows, and no more than 15% of the room's total floor area for spaces with fewer or no windows. In Hawaiʻi it is recommended that skylights not be used in homes unless necessary, due to the heat gains associated with them. Atriums are open spaces like a courtyard or main room that rise up from within a building and are sometimes covered with a skylight or glass, or sometimes left open to the environment. Atriums and skylights have the same illumination properties, though atriums are usually of a larger scale than most skylights. Roof monitors bring light into a space from the roof through the use of angled mirrors which collect the light and direct it into the building. There are also specialized transportation systems to collect and redistribute light including light wells or tubes and heliostats.

Windows can be either fixed, as in a picture window, or operable. Fixed or picture windows do not let in any natural ventilation, but have a higher U-factor than operable windows due to a tighter air seal around the window. Operable windows are necessary in Hawaiʻi to capture the prevailing natural breezes. The operable types of windows include casement windows, awning windows, hopper windows, horizontal slider windows, single and double-hung windows and louvered windows. Hinged windows such as awnings, hoppers and casements generally have lower air leakage rates than sliding windows because the sash closes by pressing against the frame. Hinged windows also have the advantage of being able to fully open and provide better ventilation than sliding windows. Sliding windows are limited to a maximum opening of half the window size. Casement windows provide the greatest user operability and source of ventilation; unfortunately they are also the most expensive choice in window opening. They project outward and act as a wing wall to catch the prevailing breezes and direct them into the interior of the building.

This project will use a combination of picture, casement, awning and louvered windows. Very few of the windows will be picture windows, since the homes will require maximum access to natural ventilation for thermal comfort. The only fixed windows will be in the center of the clerestory windows which are not used for ventilation. Casement, awning and louvered windows are all used at body level within the home to capture prevailing winds and provide natural ventilation.

## 5.1d Daylighting Design

Honolulu Housing Code Section 27-4.4 Light--Ventilation

(a) Natural Light and Ventilation.

(1) All guest rooms and habitable rooms within a dwelling unit or congregate residence shall be provided with natural light by means of windows or skylights with an area of not less than 1/10 of the floor area of such rooms with a minimum of 10 square feet. Not less than 1/2 of the required window or skylight area shall be openable to provide natural ventilation.

The final green house model far exceeds the minimum requirements of window area from the Honolulu Housing Code. For both plan types bedroom two has the lowest percentage of window area to floor area with 28% for plan one, and 24% for plan two. Bedroom three has the highest percentage at 63% for plan one, and 62% for plan 2. The goal for this project was to provide at least 30% more natural light access than what the Honolulu city code demands. Overall plan one has a total of 43% window area to floor area, which is in increase of 33% over the minimum. Plan two has a total of 40% window area to floor area, which is an increase of 30% over the minimum.

The daylighting design for this project has evolved from the design and analysis of the base case house model, the first green house model and then the final green house model. With each design, data was collected, analyzed and then redesigned to show quantifiable improvements. Each of the design models in Ecotect was analyzed for daylighting levels in Lux and daylight factor throughout the year. The kitchen/living area of the final green house model was rendered using Radiance to show daylight levels in Lux, and to show how the space would look from daylight alone. In addition, solar penetration images are shown for each of the bedrooms and the kitchen/living area.

The base case model and the final green house model receive similar levels of daylight in the interior; however the final green house model receives higher levels farther into the interior of the house. The base case model shows that the daylight is concentrated close to the windows and does not penetrate as deep into the interior as the final green house model (*see Figs. 5.1.5 – 5.1.8*). The final green house will have more uniform lighting throughout the space, which will reduce the effect of intense light and dark zones.

Every space in the final green house model achieves minimum daylight factor requirements of 2% for daylit spaces. The space that receives the lowest daylight factor percentage is bedroom two, which receives a yearly average of 3.96%. The master bedroom also meets the daylit requirements with a yearly daylight factor of 4.07%. Bedroom three receives the highest daylight factor at 8.45% for the year. The kitchen/living area (6.08% daylight factor) and bedroom three (8.45% daylight factor) both meet the minimum requirements of 5% daylight factor for well daylit spaces (*see Figs. 5.1.9 – 5.1.18*).

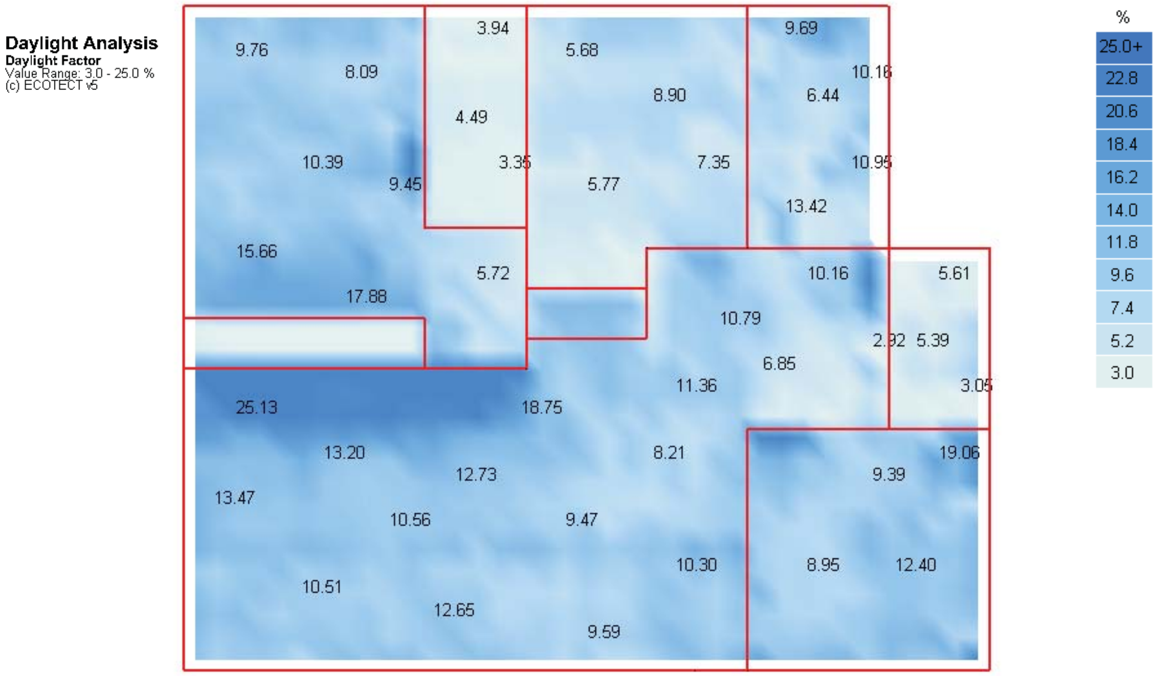



Fig. 5.1.5 -Plan view showing the annual average daylight factor percentages for the final green house model. The scale on the right goes from a low (grey) of 3% to high (blue ) of 25+%.

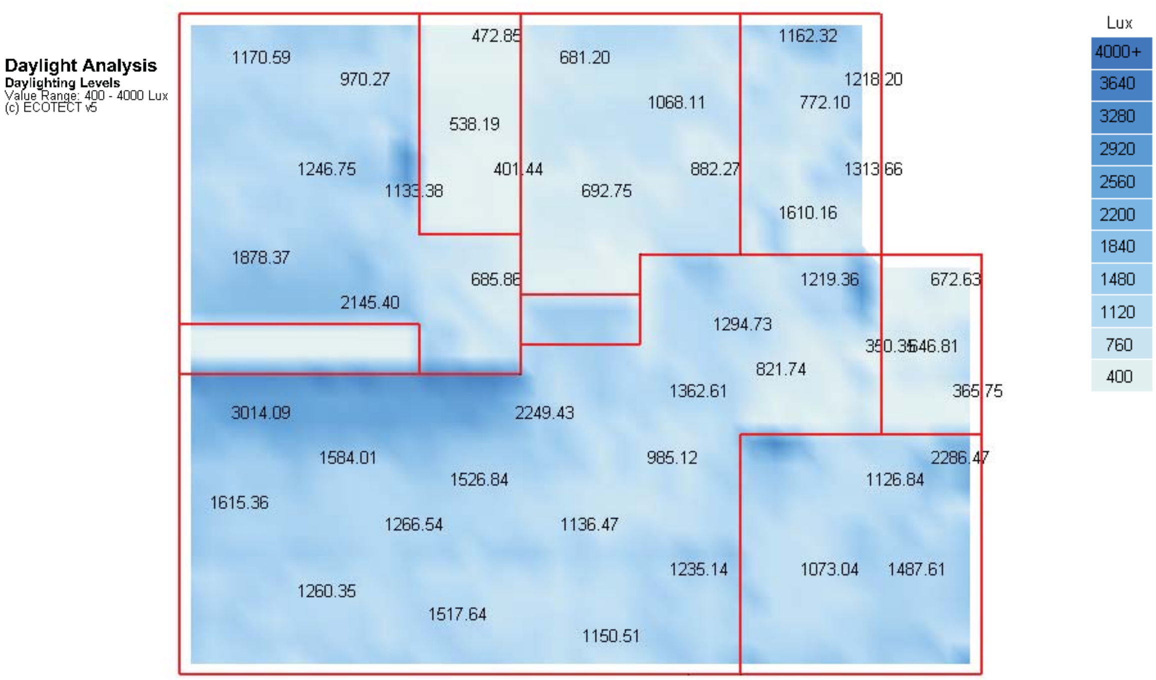



Fig. 5.1.6 -Plan view showing the annual average daylighting levels in Lux for the final green house model. The scale on the right goes from a low (grey) of 400 to a high (blue) of 4000+ Lux. The numbers throughout the image show the Lux levels at each location.

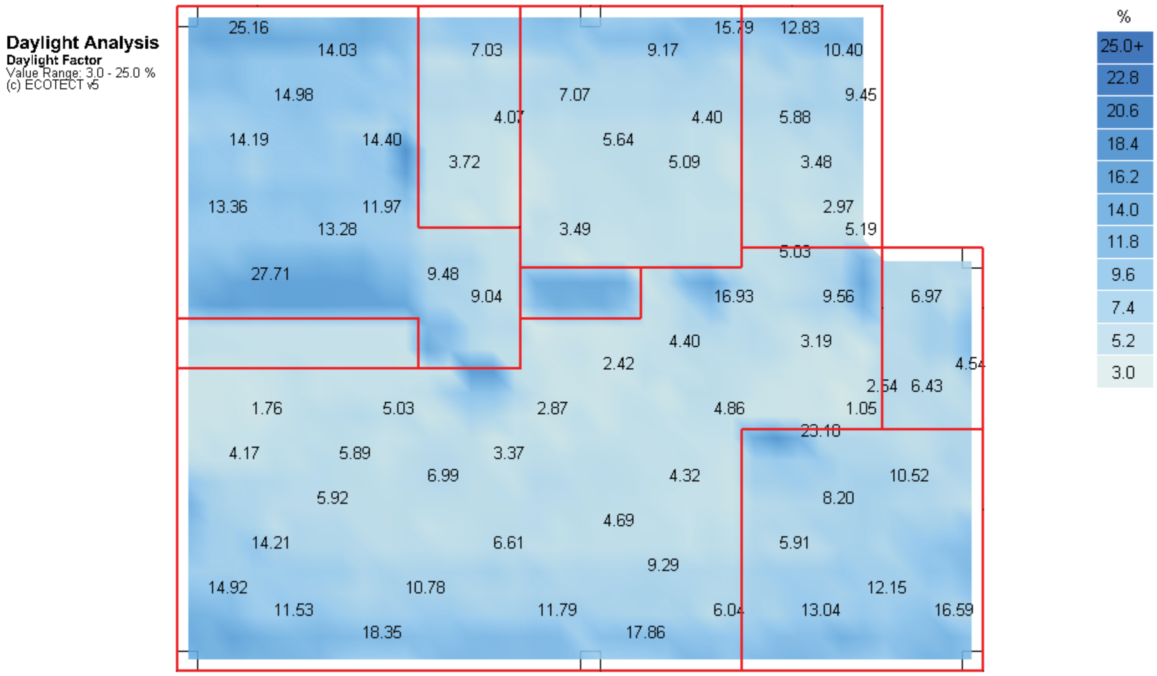



Fig. 5.1.7 -Plan view showing the annual average daylight factor percentages for the base case house model. The scale on the right goes from a low (grey) of 3% to high (blue ) of 25+%.

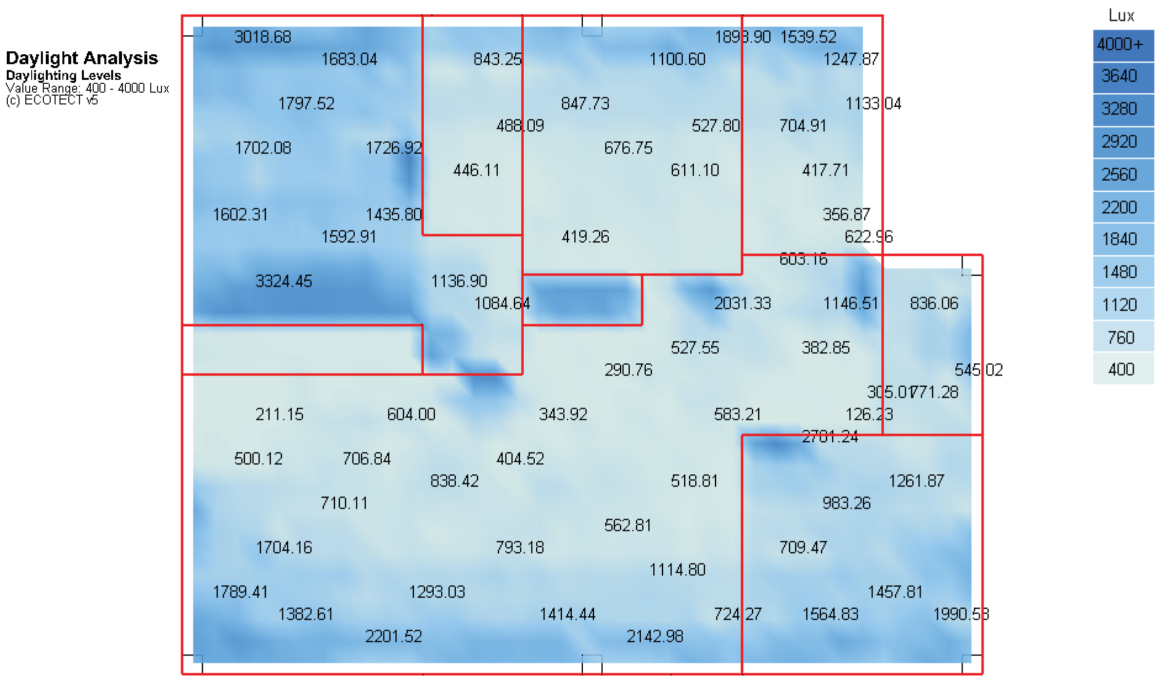



Fig. 5.1.8 -Plan view showing the annual average daylighting levels in Lux for the base case house model. The scale on the right goes from a low (grey) of 400 to a high (blue) of 4000+ Lux. The numbers throughout the image show the Lux levels at each location.

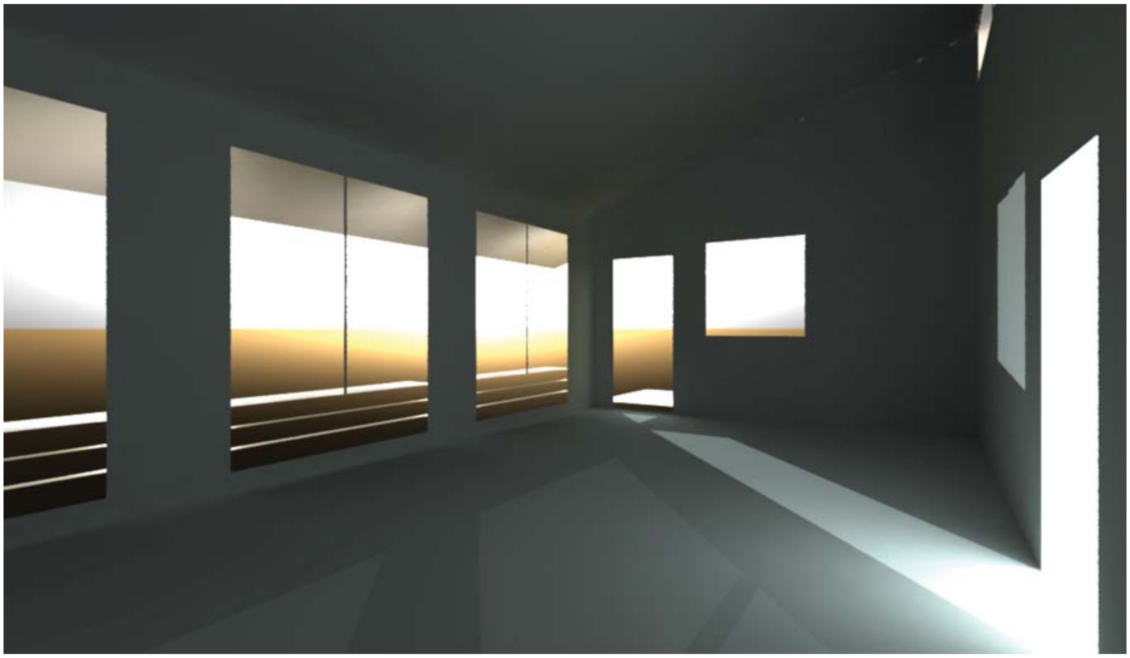


Fig. 5.1.9 -Radiance image looking south of the **KITCHEN-LIVING AREA** at 4:30pm on December 21.

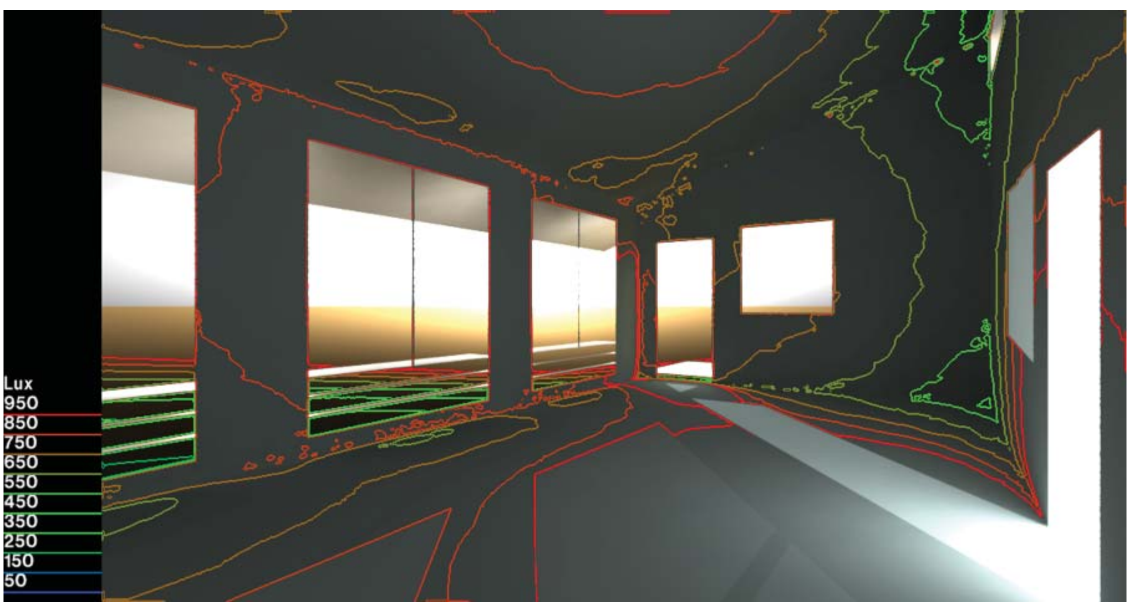



Fig. 5.1.10 -Radiance image looking South of the **KITCHEN-LIVING AREA** at 4:30pm on December 21. This image shows the Lux levels throughout the space from daylight.

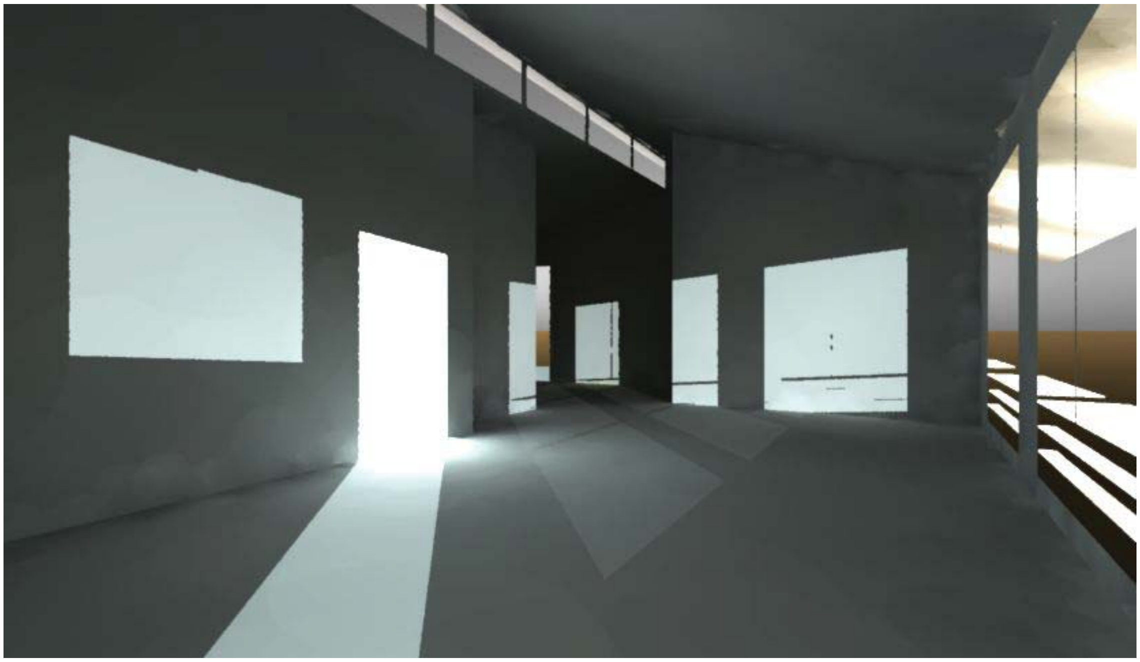


Fig. 5.1.11 -Radiance image looking East of the **KITCHEN-LIVING AREA** at 4:30pm on December 21.

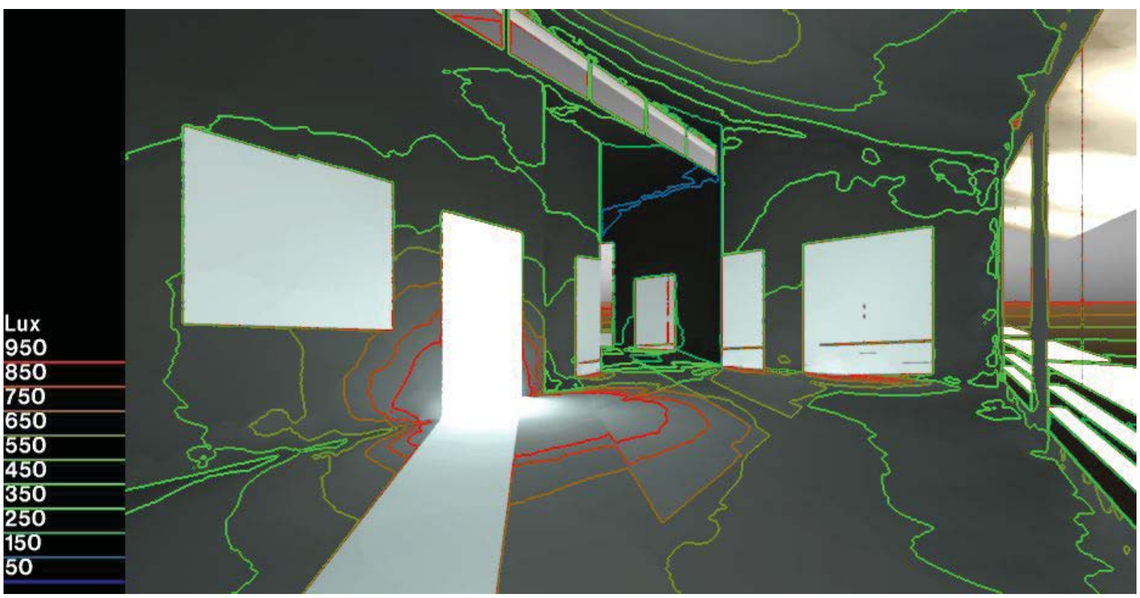
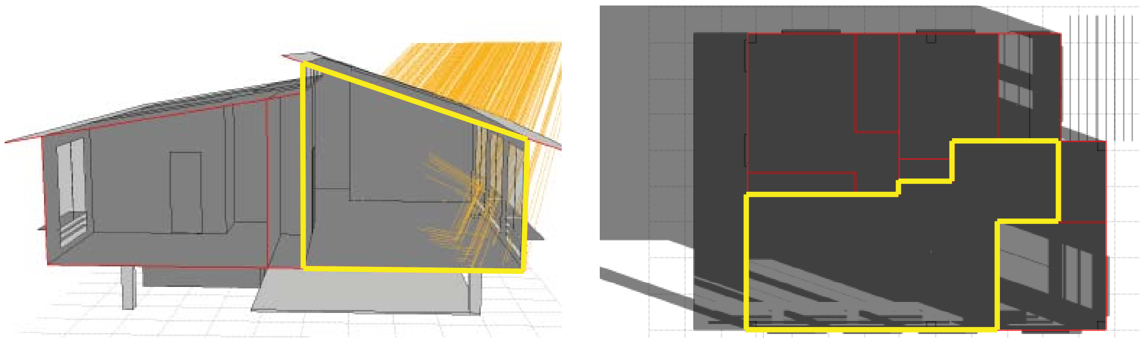
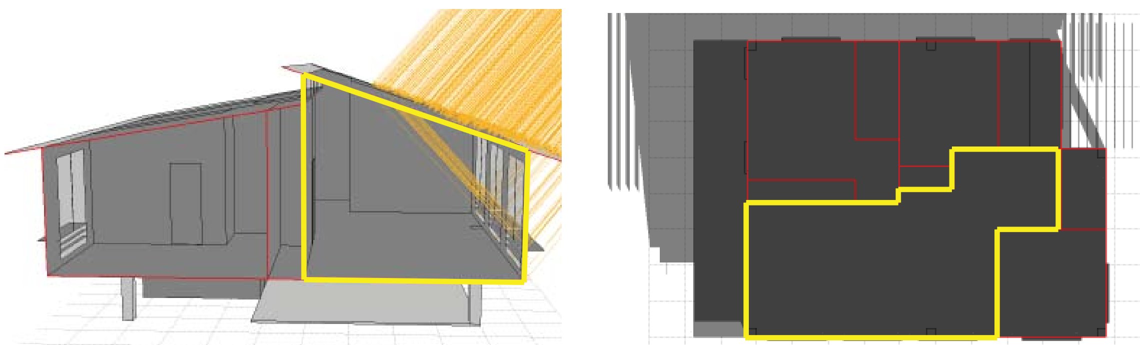


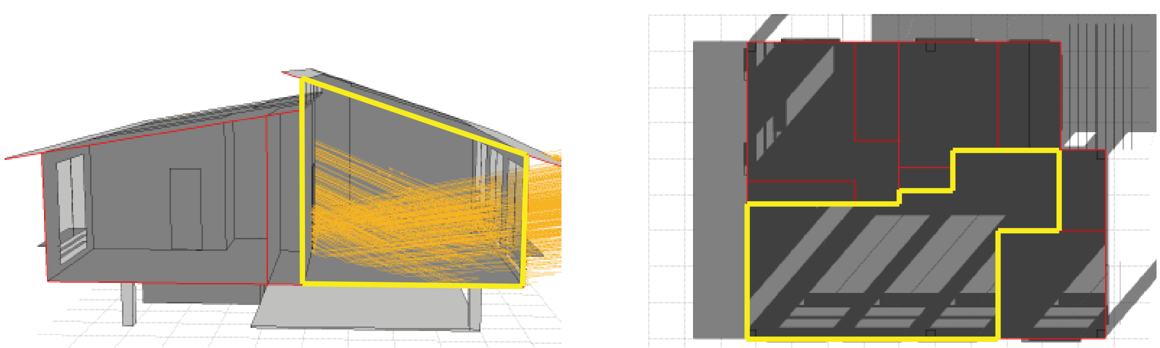

Fig. 5.1.12 -Radiance image looking East of the **KITCHEN-LIVING AREA** at 4:30pm on December 21. This image shows the Lux levels throughout the space from daylight.



December 21 - 8:15am

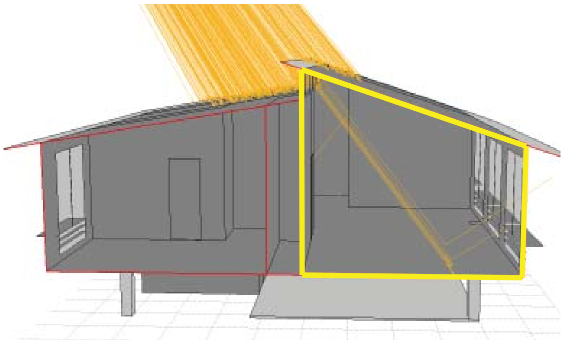


December 21 - noon

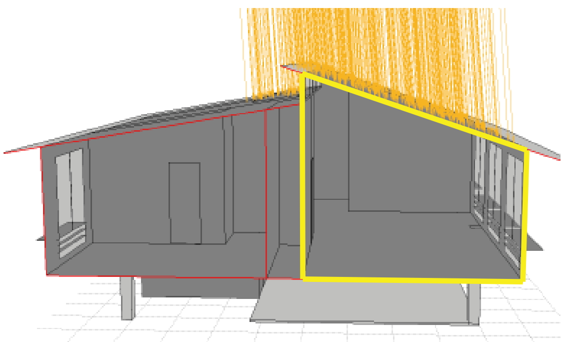


December 21 - 4:45pm

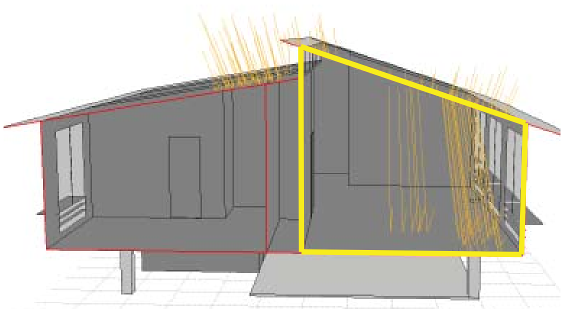
Fig. 5.1.13 -Views of the **KITCHEN-LIVING AREA** showing direct solar exposure on Dec 21 at 8:15am, noon, and 4:45pm. The kitchen-living area receives excellent daylight throughout the year, with an average daylight factor for the year of 6.08%, which is above the minimum 5% for well daylight spaces.



June 21 - 8:15am

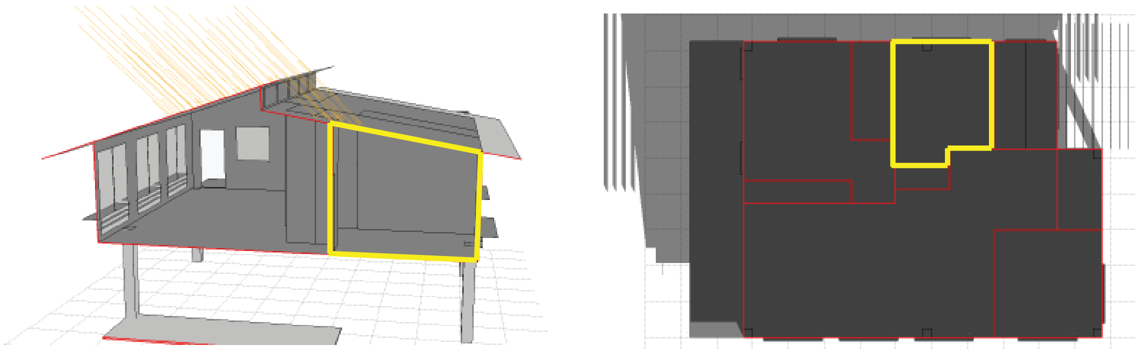


June 21 - noon

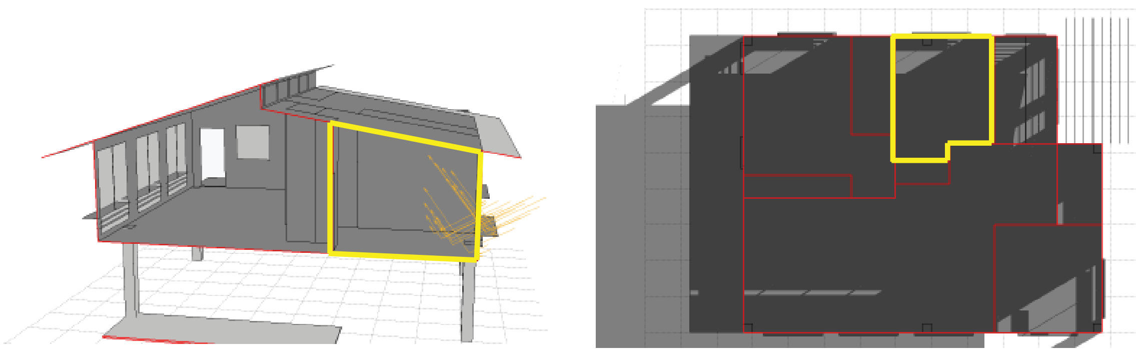


June 21 - 5:15pm

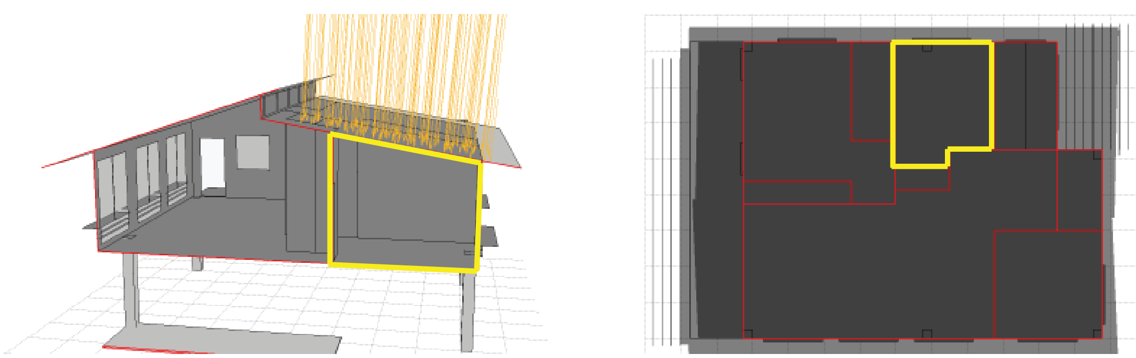
Fig. 5.1.14 -Views of the **KITCHEN-LIVING AREA** showing direct solar exposure on June 21 at 8:15am, noon, and 5:15pm.  This space receives the second highest amount of daylight of all the spaces, which is important because the space will be used more during daylight hours than the other spaces of the home.



December 21 - noon

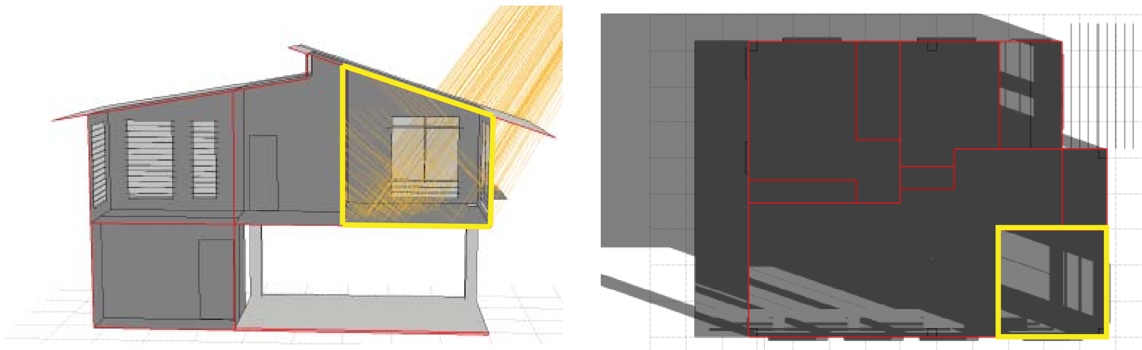


June 21 - 8:15am

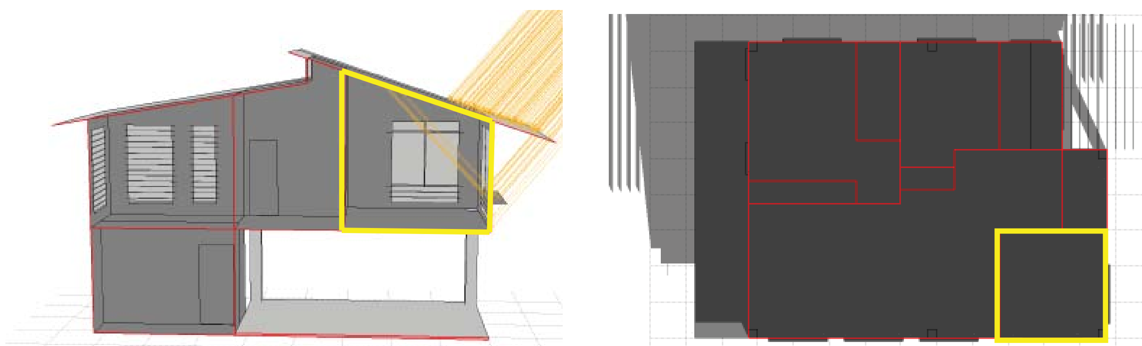


June 21 - noon

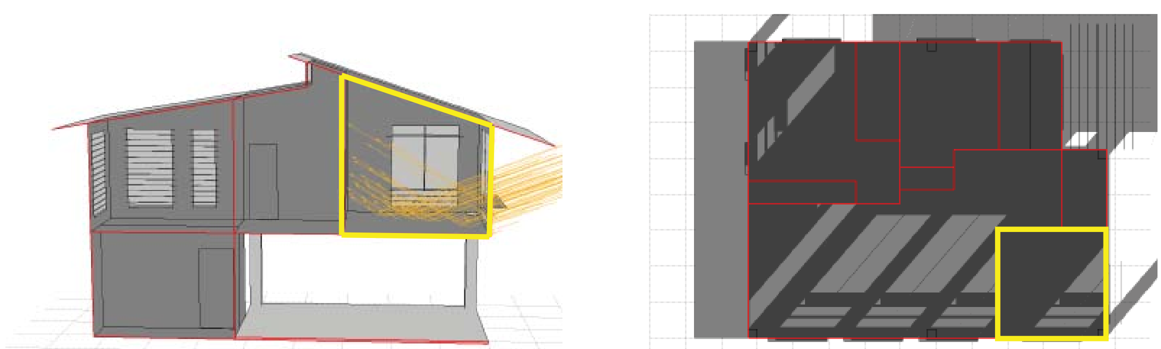
Fig. 5.1.15 -Views of **BEDROOM 2** showing direct solar exposure on Dec 21 at noon, June 21 at 8:15am, and June 21 at noon.  Bedroom 2 is shaded during most of the day, for most of the year.  The average daylight factor for the year is 3.96%, which is above the minimum 2% for daylit spaces, but under the 5% requirement for well daylit spaces.



December 21 - 9:30am

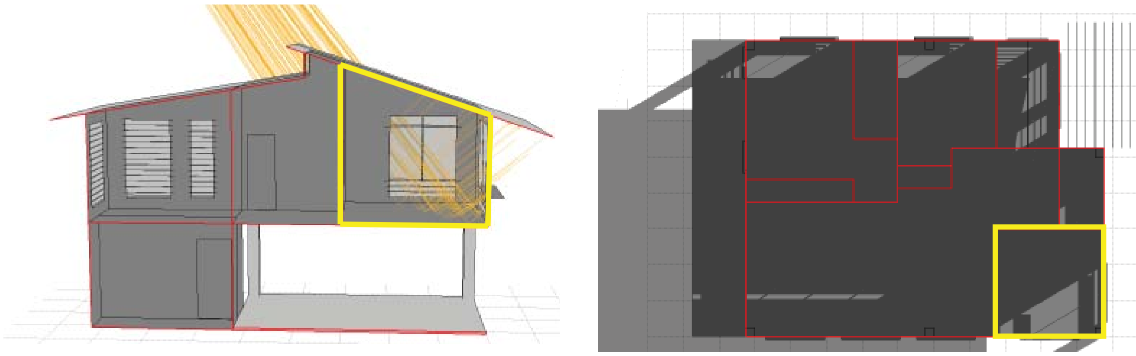


December 21 - noon

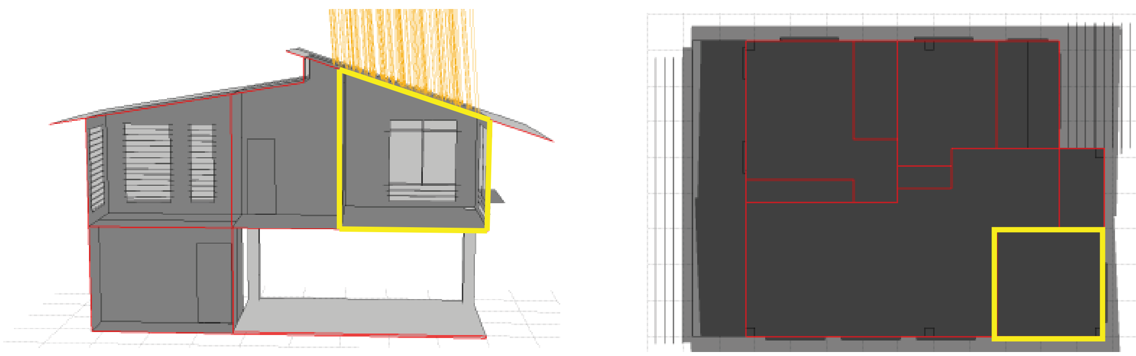


December 21 - 4:00pm

Fig. 5.1.16 -Views of **BEDROOM 3** showing direct solar exposure on Dec 21 at 9:30am, noon, and 4:00pm.  Bedroom 3 receives the highest amount of daylight due to it's locattion on the south-east corner of the house.  The average daylight factor for for the year is 8.45%, which is well above the minimum 5% for well daylit spaces.

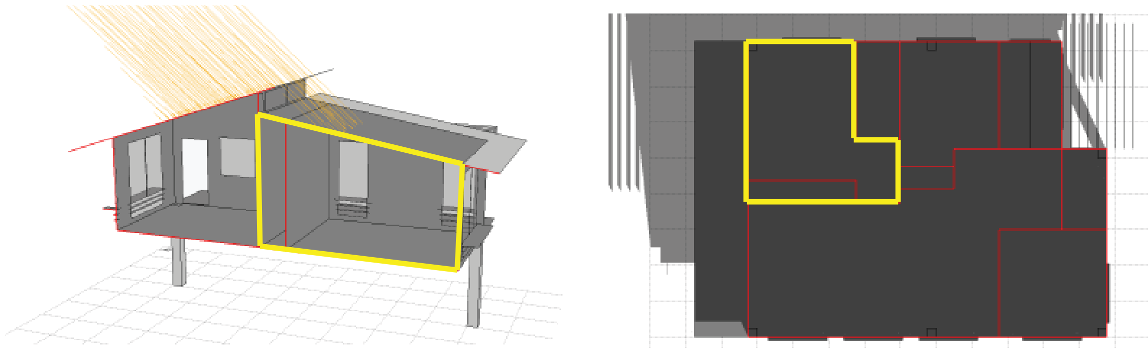


June 21 - 8:15am

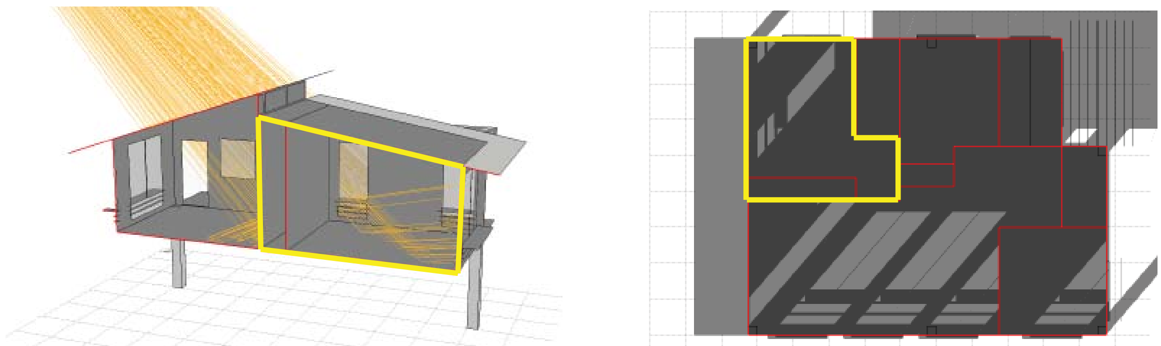


June 21 - noon

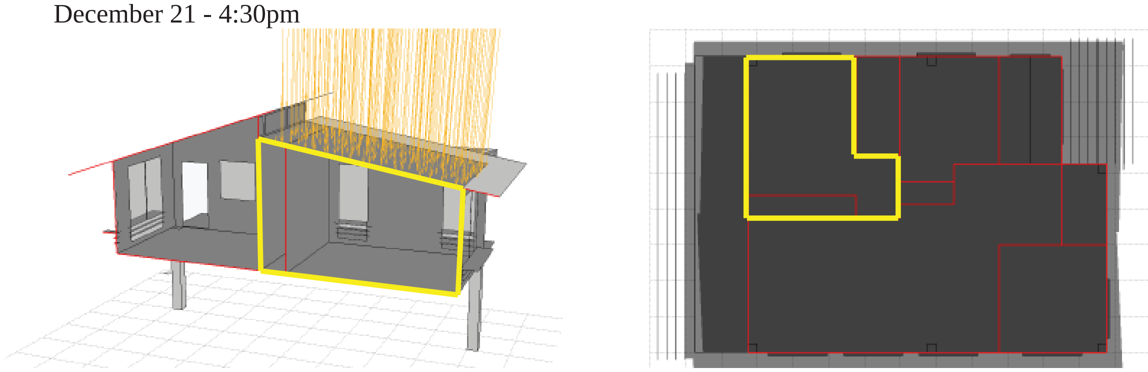
Fig. 5.1.17 -Views of **BEDROOM 3** showing direct solar exposure on June 21 at 8:15am, and noon. Due to the sun's position in the sky, there is more daylight in this room during the winter months, than in the summer.



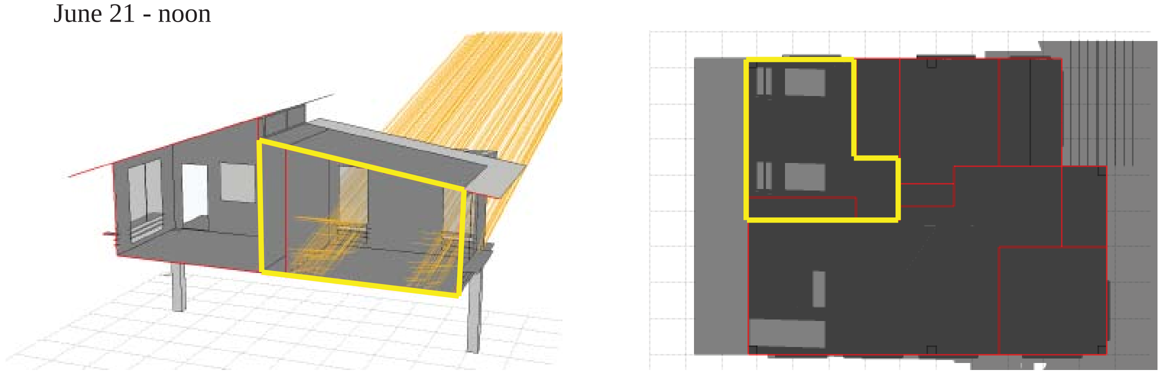
December 21 - noon



December 21 - 4:30pm



June 21 - noon



June 21 - 6:00pm

Fig. 5.1.18 -Views of the **MASTER BEDROOM** showing direct solar exposure on Dec 21 at noon and 4:30pm, and on June 21 at noon and 6:00pm. The average daylight factor for the year is 4.07%, which is above the minimum 2% for daylit spaces, but below the well daylit level of 5%.

## ***5.2 APPLIANCES AND LIGHTING***

### 5.2a Appliances

The first step in minimizing heat generated in the home is to choose energy efficient appliances. The less efficient an appliance is the more waste heat it generates. Therefore choosing energy efficient appliances will help save energy and money; it saves money due to less energy being used, and also saves money on having to actively cool the interior of the home.

All of the appliances designed for this project will be ENERGY STAR rated, except for the clothes dryers and the ranges/ovens which are not yet qualified for the ENERGY STAR program. Installing ENERGY STAR appliances and lighting will save the homeowner money on annual electric bills and water bills, and help the home qualify for Energy Star and LEED certifications. All appliances that are ENERGY STAR rated have far exceeded national minimum energy standards, and most are above ENERGY STAR minimums. Most appliance manufacturers have product information pertaining to energy efficiency and water efficiency. ENERGY STAR has compiled lists of leading manufacturers for qualified products which gives information on model numbers, kilowatt-hours per year (kWh) used, the energy factor, less % energy, and water factor.

Refrigerator-

The ENERGY STAR standards for refrigerator freezers require that all refrigerators greater than 7.75 cubic feet must be at least 20% more efficient than the federal minimum standard. This standard was increased by ENERGY STAR in April 2008; the previous requirement was 15 % more efficient. ENERGY STAR qualified refrigerators use about half as much energy as models manufactured before 1993 (ENERGY STAR). The model chosen for the project homes is the GE Energy Star 21.0 Cu. Ft. Stainless Top-Freezer Refrigerator, model number GTH21SCXSS. This model uses an estimated 415 kWh per year, which GE estimates to cost approximately $44 per year (GE Appliances). This price is based on the 2010 national average of 10.7 cents per kWh. In Honolulu, based on the 2010 average of 25.5 cents per kWh, this would increase the annual cost of the refrigerator to $106. Top-freezer refrigerators are considerably more energy efficient than side-by-side refrigerator freezers which have annual kWh usage ranging from a low of 540 kWh up to 613 kWh. The National Appliance Energy Conservation Act (NAECA) national standard for a 22 cubic foot refrigerator is 519 kWh per year. The GE model suggested here is 20% more efficient, meeting the ENERGY STAR standard.

Dishwasher-

ENERGY STAR qualified dishwashers use about 10% less energy than the national minimum standard for energy consumption. Dishwashers will be a standard feature in each kitchen in the project. ASKO is a leader in energy efficient and water efficient dishwashers in the industry. ASKO dishwashers range from 63% to 102% more energy efficient than federal standards (ASKO Appliances). The dishwasher model chosen for this project is the ASKO D3251HD. This model consumes an estimated 231 kWh per year, which is 29% more efficient than ENERGY STAR standards and 35% more efficient than the national standards. The estimated kWh are based on a typical usage of 215 loads per year. In Hawai‘i the annual cost of operating this dishwasher would be $64. The old national minimum energy factor for a dishwasher is 0.46. This model has an energy factor of 0.93, 102% better than the minimum standard. The federal minimum standards for dishwashers was increased from 0.46 EF to a maximum of 355 kWh/yr and 6.5 gallons/cycle effective January 1, 2010. Both ENERGY STAR and the federal standard will be using a maximum annual kWh requirement instead of EF (CEE Forum). ENERGY STAR sets maximum energy and water usage for dishwashers at 324 kWh/yr and 5.8 gallons/cycle. The ENERGY STAR standards will be increased again in early 2012.

Clothes Washer and Dryer-

ENERGY STAR qualified clothes washers use about 30% less energy and at least 50% less water than regular non rated washers (ENERGY STAR). The two main factors to look for in an ENERGY STAR rated clothes washer is a model with a high Modified Energy Factor (MEF) and a low Water Factor (WF). MEF is a measure of energy efficiency from energy used by the washer, heating the water and running the dryer. Both the washer and dryer models chosen for this project are from GE, and both are chosen for their energy performance, water efficiency and cost effectiveness. The clothes washer model is the GE ENERGY STAR 4.0 IEC Cu. Ft., model number WBVH5300KWW. It is estimated that this washer will use 131 kWh per year based on an average of eight loads per week. The estimated yearly cost of operating this washer is $14, based on a national average electric cost of 10.65 cents per kWh. In Hawaii, with an electric cost of 25.5 cents per kWh, this washer would cost about $33 for the year. The MEF for this washer is 2.32, 46% more efficient than federal standards, and the WF is 3.75, which uses 61% less water than the federal maximum. Both of these metrics are the highest rated for all GE energy efficient washers (GE Appliances).

The performance of the dryer will not be taken into effect because ENERGY STAR does not rate dryers at this time. There is also no provided data on the efficiency of dryers by the manufacturers to base a decision. The model chosen is the matching set for the clothes washer, the GE 7.0 Cu. Ft. Super Capacity Electric Dryer, model number DBVH520EJWW. This model features a moisture sensor, which will stop the machine when the clothes are dry to save energy from extended cycles.

Range/Oven-

Unfortunately, ranges and ovens are not ENERGY STAR qualified appliances, and there is no provided data about the energy efficiency of these on which to base decisions. The range/oven combination chosen for this project is based on size, price, and coordination of appliances in the kitchen. The model chosen is the GE 30” Slide in Electric Range, model number JSP39SNSS.

Solar Water Heater and Collectors-

The solar water system chosen for this project is the 80 gallon EnerWorks Focus Single Tank and active solar collectors from EnerWorks Appliance. The 80 gallon tank is sized for a typical family of four. This system is designed for tropical climate installations where there is no freezing. The water heater uses a combination of solar storage and electric auxiliary to provide hot water at all times, using electric heating only when necessary. The Focus Single Tank system comes with two roof mounted solar collectors, each measuring four feet wide by eight feet long and three inches thick. The low profile solar collectors are designed to look more like skylights to reduce the look of bulky equipment on the roof (EnerWorks).

### 5.2c Lighting

All of the lighting used in the homes, including ceiling fans, have been selected due to their earning the ENERGY STAR certification. The lighting chosen for this project is from the lighting company American Fluorescent. The ceiling fans and bathroom fans are from Hunter Fan. The fixtures specified include fluorescent strip lighting, outdoor sconces, flush ceiling mount lights, vanity lights, wall sconces, pendant lamps, under cabinet lights and ceiling fans with lamps. Each of the specified lighting fixtures use fluorescent bulbs except the under cabinet lights which are 1W single bulb LED lamps.

The bedrooms in the project are designed with Hunter Palermo ceiling fans with lamps. This fan uses a single 22W CFL bulb, which also has dimming capabilities. The kitchen is designed with three lamp pendant lights over the island; each fixture houses a single 13W CFQ lamp. In addition, the kitchen has under cabinet 1W LED lamps to provide lighting at counter level. The main living areas and the entry have additional ambient light provided by wall sconces, which each use two 13W CFQ lamps. The bathrooms use three lamp vanity fixtures; each of the bulbs is an 18W self-ballasted lamp. The carports will have two linear fluorescent fixtures, which each use two F17T8 lamps (17W each). Each porch and lanai will have outdoor rated wall sconces, which each use two 13W CFQ lamps.

Through the daylight strategies used in this project, the electric lighting will be obviated during the day for most of the year, and with the energy efficient electric lighting specified the homeowner can expect greatly reduced electric bills. A typical incandescent lamp uses 60-100W of power and last between 750-1000 hours. The compact fluorescent lamps used in this project in comparison use at most 22W and last up to 20,000 hours (Buy Lighting). A typical 13W CFQ bulb will last about 10,000 hours. The lifetime cost of one fluorescent bulb in Hawaii is about $47, compared to 10 incandescent bulbs needed to equal the life of the fluorescent bulb at a total cost of about $164. This is based on a 60W incandescent bulb cost of $0.50 and a lifetime of 1,000 hours, a 13W CFQ bulb cost of $3.00 and a lifetime of 10,000 hours and the 2010 Honolulu electric rate of $0.25 per kWh. Using one CFQ lamp instead of 10 incandescent bulbs will save $117 and will use about 75% less electricity. Another eco-friendly option is replacing CFQ lamps with equal wattage LED lamps. A 13W LED lamp costs around $50, but has a lifetime of over 50,000 hours and they do not contain the toxic chemical mercury that fluorescent lamps do.

## ***5.3 SOLAR WATER HEATING***

Solar water heaters are a proven cost-effective way of generating hot water for a home. In Hawai‘i, water heating is the largest single factor of electricity in a home, except for homes with mechanical conditioning systems, and usually accounts for 1/3 of the monthly electric bill. Installing a solar water heater in Hawai‘i can supply an average of 80%-90% of the home’s annual water heating needs (Hawaii Energy). Systems are built to last a minimum of 15 years with regular maintenance. The savings on annual electric bills over the life of the system far outweighs the initial cost of the system, and will be saving the homeowner money for years. Using the sun’s energy to heat water is efficient, saves money and reduces pollution. In fact, each residential system can save approximately 227 gallons of oil annually (Hawaiian Island Solar).

Solar collectors absorb heat from the sun and transfer the absorbed solar heat to water circulated through the collectors. For homes in Hawai‘i, the collectors are usually located on a south-facing roof, which is the optimal orientation for solar potential. The heated water is then stored for use throughout the day and night in a hot water storage tank. There are passive and active solar water systems available. The passive type acts as a thermosiphon by moving the water through the collector using natural convection. Hot water naturally rises, so there is no need for a mechanical pump to help circulate the water. However, with this system the storage tank needs to be above the collector and therefore sits on the roof with the collector. This system creates added weight to the roof and can be an eyesore for the design of the home. The active system forces the water circulation through the collector using an electrical pump. The pump is controlled by temperature sensors and a differential controller to turn the pump off and on. The pump will turn on when the water in the collector is sufficiently hotter than the water at the bottom of the storage tank. To be even more efficient, a system can be installed with a small photovoltaic panel to produce DC current to help power the pump. With this system the sun will strike the PV panel enough to power the pump, and at the same time the water is usually hot enough to be moved to the storage tank.

The cost for solar water heating systems are relatively inexpensive compared to the savings that they will produce. In addition to the annual electric savings, there are both Hawai‘i state tax and federal tax credits which will help offset the initial cost. The Hawaii Renewable Energy Tax Credit for single family residences is 35% of actual cost, with a maximum credit of $2,250. The credit is effective for any system installed after June 1, 2006. According to the DBEDT of the State of Hawai‘i, “solar water heating systems can save the average homeowner about 30%-50% on monthly utility bills”. The Federal Energy Policy Act of 2005, signed by President Bush on August 8, 2005, gives homeowners who purchase and install solar water heaters a 30% tax rebate, or up to $2,000. The tax credit program was implemented in an effort to promote the use of solar energy and minimize our need for foreign oil. In addition to the tax credits, the Hawaiian Electric Company (HECO) provides a $750 rebate towards the cost of the solar water system.

An example of the initial cost shows the immediate savings:

| | |
|---|---|
| Gross Cost | $5,000 |
| Utility Rebate | -$750 |
| Subtotal | $4,250 |
| HI tax credit (35%) | -$1,487 |
| Fed. Tax credit (30%) | -$1,275 |
| Net Cost | $1,488 |

Hawai‘i was the first state to pass a bill requiring solar water heating systems in new homes. The bill was signed into law by Hawai‘i Governor Linda Lingle. The law, which was put into effect in 2010, requires all new homes to install solar water heaters. Unfortunately, due to the requirement for all new homes to be equipped with a solar water heating system, the $750 HECO rebate is not available for new construction.

## *5.4 RAINWATER CATCHMENT*

Rainwater collected on a building's site can be used for drinking, bathing, washing, flushing, laundry and gardening. However, if the system is not properly designed and maintained, it can be a source of health risks and illness. Because of the many different climate zones of Hawai'i, there are locations that have more than enough rainfall to sustain a building year-round, and other locations where a system is economically unfeasible. The first step in figuring the potential effectiveness of a rainwater catchment system for a site is to study the rainfall patterns in the particular microclimate of the site.

The area of Waianae, Oahu, is very dry with an average annual rainfall less than 30 inches. The month with the most rainfall is January, with less than four inches for the month, and the least rainfall occurs in August with less than one inch of rainfall. To calculate the effectiveness of a rainwater catchment system for a home, you will need to know the roof square footage, the amount of rainfall for the building's microclimate and the amount of water needed throughout the year.

There is a simple calculation for estimating the potential rainfall that a building can catch. A square foot of horizontal surface receives approximately 0.625 gallons of water with each inch of rainfall (Macomber, 11). To calculate the effective square footage of the roof that will catch rainwater, measure the width and length of the roof from eave to eave and multiply these two to get the surface area of the footprint of the roof. For example, a roof with a width of 38' and a length of 45' has 1,710 square feet of catchment area. Next multiply the amount of catchment area times 0.625 gallons, which for this example will catch 1,069 gallons per inch of rainfall. Once the amount of caught rainfall is calculated, the next step is to figure out how much catchment is possible for the site. For this example let's figure on three inches of rainfall in a month. Multiply the total gallons per inch times the amount of rainfall in a month, 1,069 gallons x 3 inches = 3,207 gallons for the month.

On average each person will use about 50-75 gallons of water per day. For a family of four that is water conscious, an average of 200 gallons will be used per day, and multiplied by 30 days for the month, a family of four will use about 6,000 gallons per month, or 73,000 gallons per year. From this example, the home is only catching about half of the monthly water need. In Waianae three inches of rainfall is about the maximum rainfall for the year, which means that at best the home will only be able to catch and use half of the average water need. When figuring on the need for rainwater catchment, it is preferable to design for the worst-case scenario, not the average or best. This is especially important for those homes that depend on rainwater catchment as the sole source of useable water.

This project has two building designs, each with different roof areas. Each building must be calculated individually to determine the amount of potential rainfall catchment.

House plan 1 roof footprint = 1,650 square feet
1,650 square feet x 0.625 (gallons/inch) = 1,031 gallons per inch of rain
1,031 gallons x 20.93 annual inches of rain = 21,579 gallons per year
21,759 is only 29.6% needed for the year on average

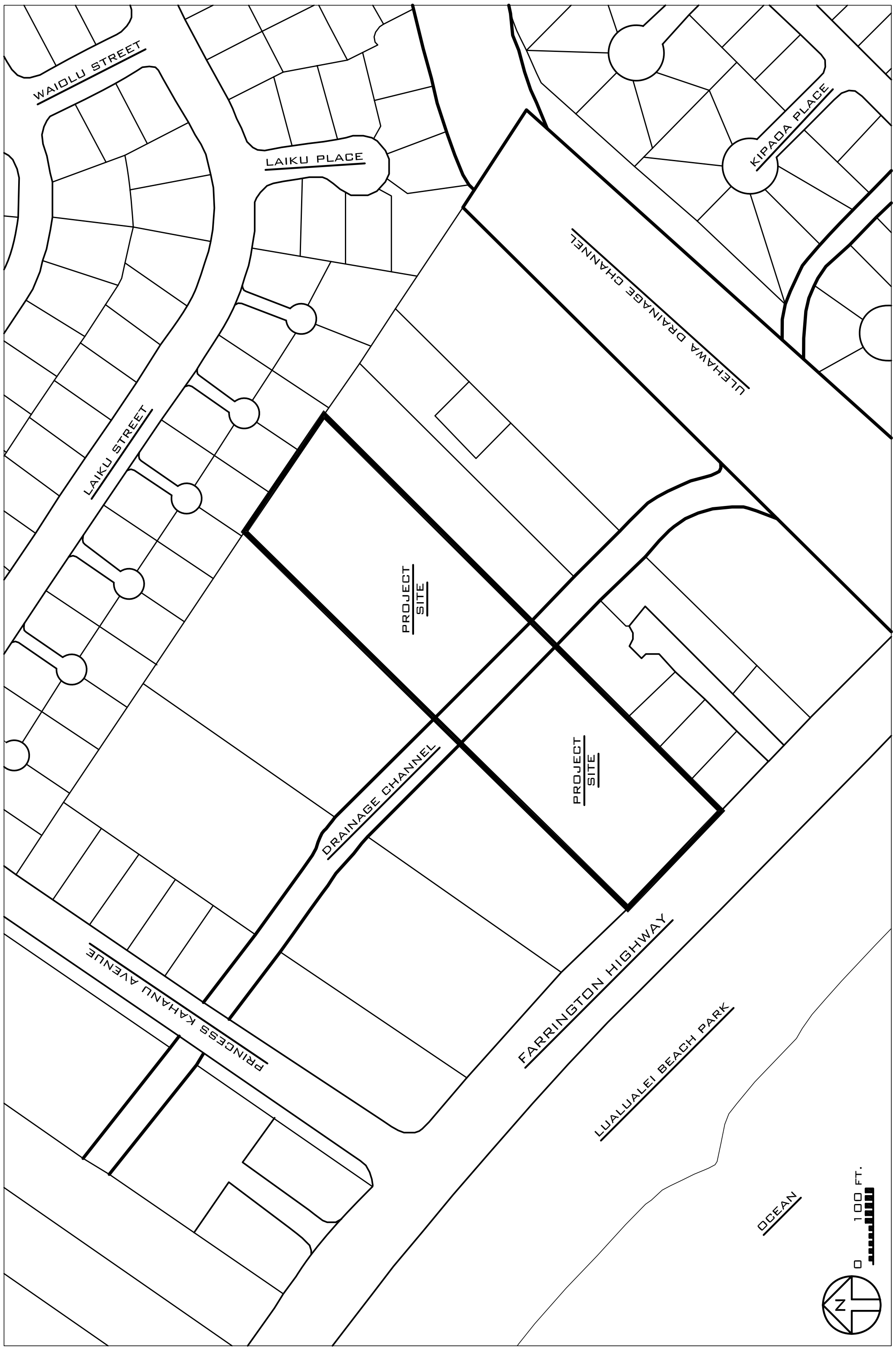
House plan 2 roof footprint = 1,050 square feet
1,050 square feet x 0.625 (gallons/inch) = 656 gallons per inch of rain
656 gallons x 20.93 annual inches of rain = 13,730 gallons per year
13,730 is only 18.8% needed for the year on average

From doing these simple calculations on potential rainwater catchment, it is clear that a rainwater catchment system will not be enough to sustain each home throughout the year. Depending on the pricing of installing a system, it is advisable to not include such a system into the design. It is possible that a small tank be designed to help with the landscaping watering of the site. Installing a rainwater catchment tank for irrigation purposes could be an optional upgrade to buyers who want their home to showcase this green technology.

# *CHAPTER 6 BUILDING DESIGN DRAWINGS*

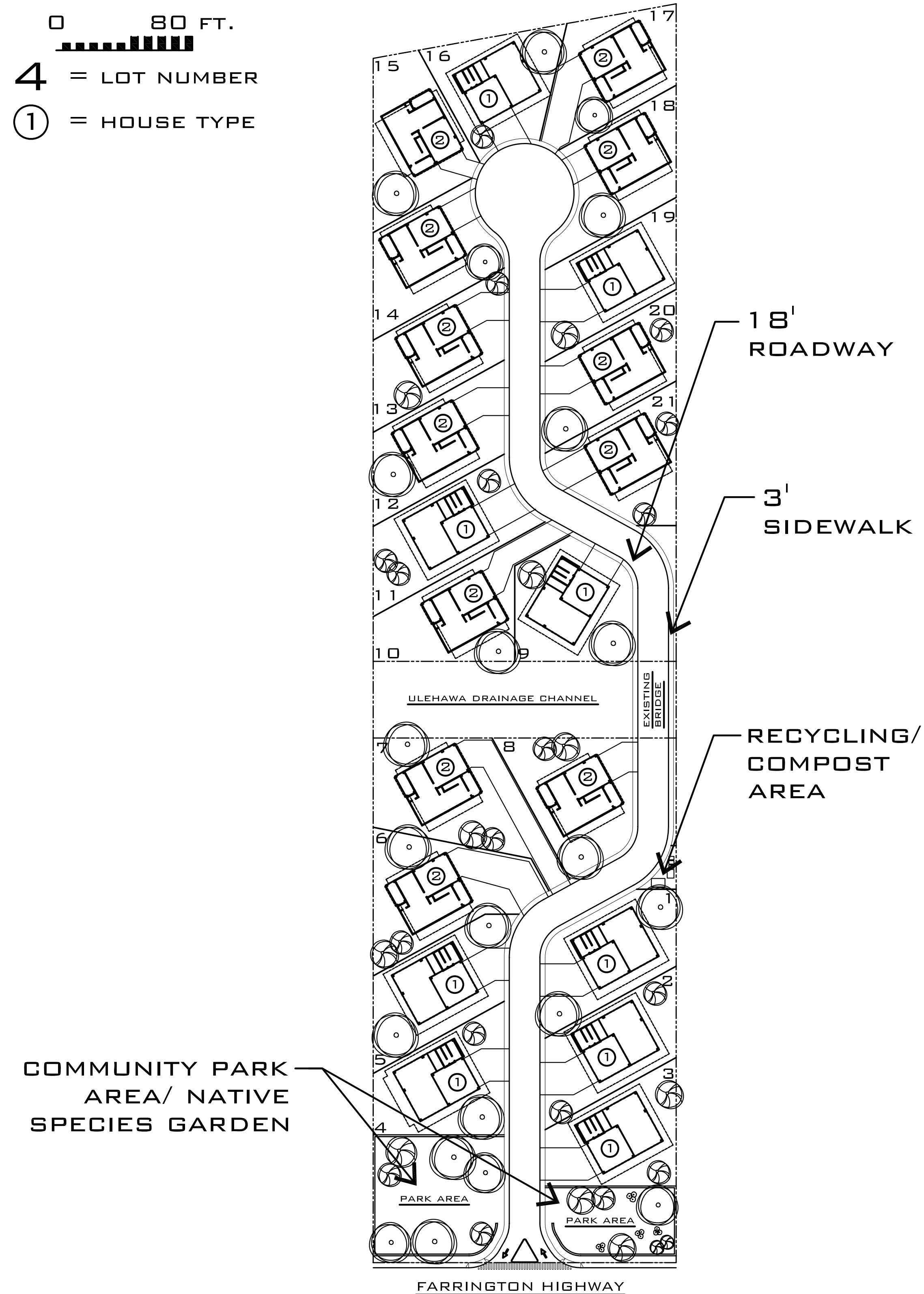
# FARRINGTON VACINITY MAP

NOT TO SCALE



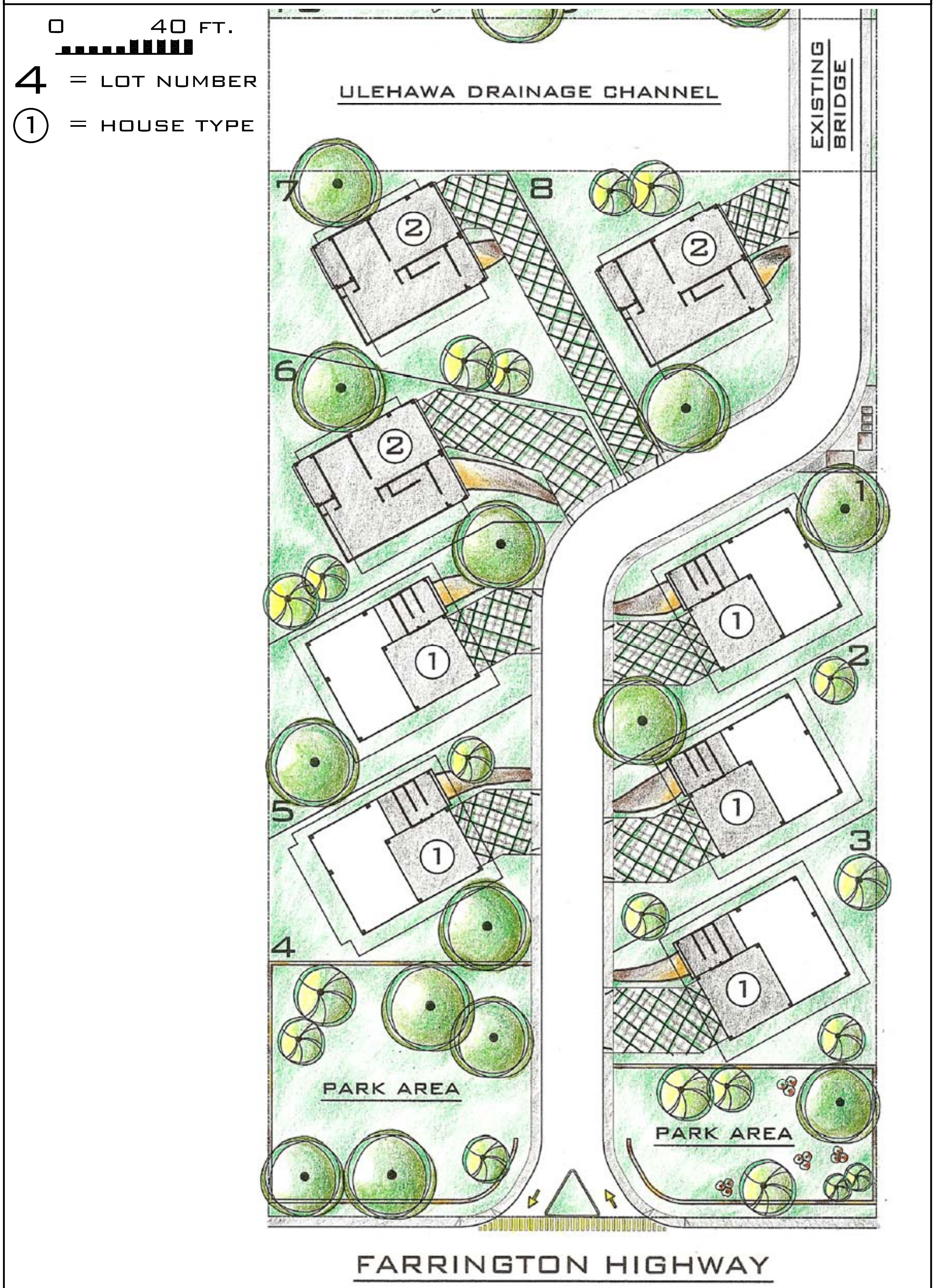
# SITE PLAN

## FULL PLAN



# MAKAI PARCEL

SITE PLAN



# MAUKA PARCEL

## SITE PLAN

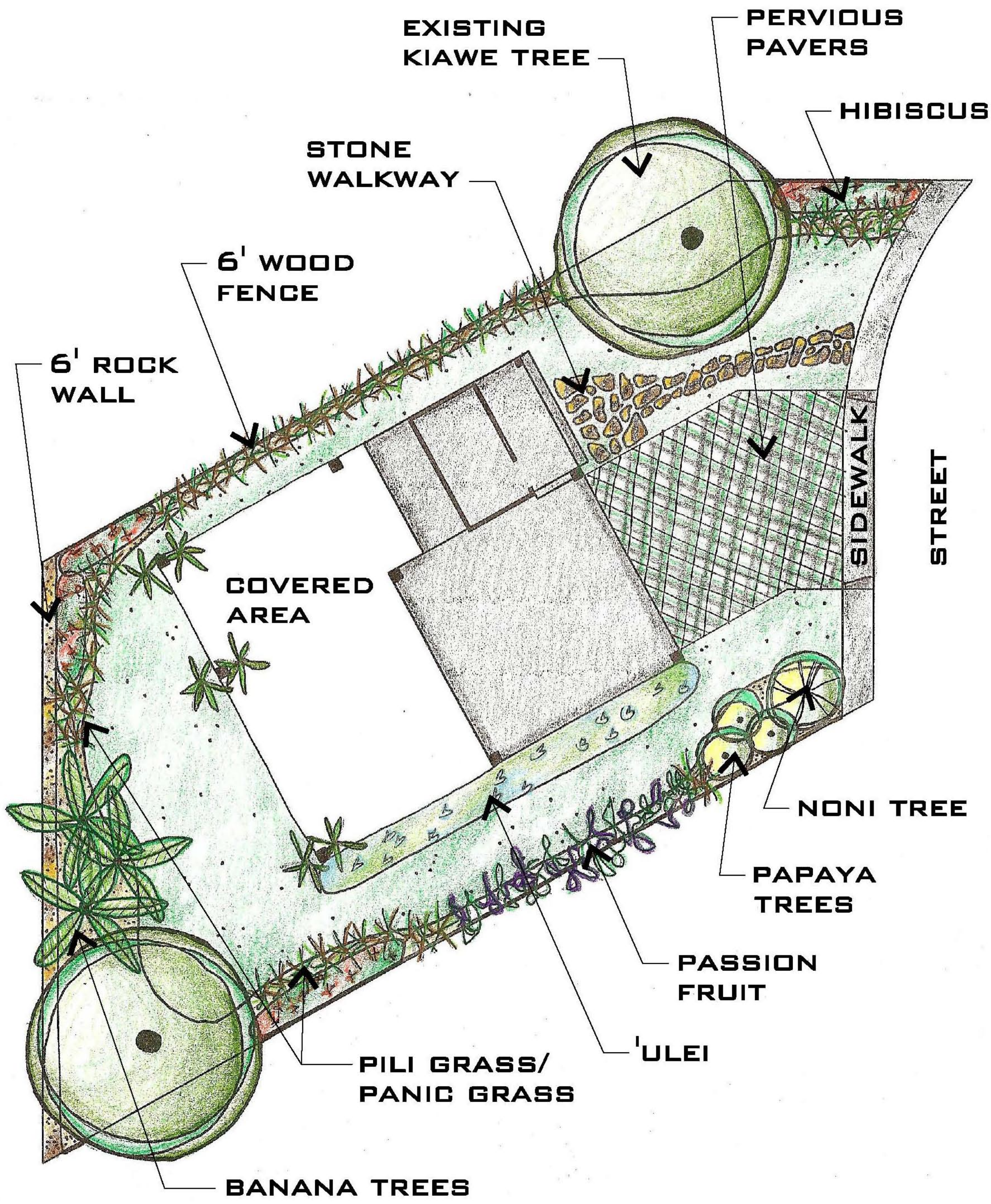
# TYPICAL LANDSCAPE PLAN

LOT 5 NOT TO SCALE

LOT 5 SPECIFICATIONS

4449 SQ. FT LOT SIZE

662 SQ. FT PAVED AREA (HOUSE & GARAGE)



# GROUND FLOOR PLAN

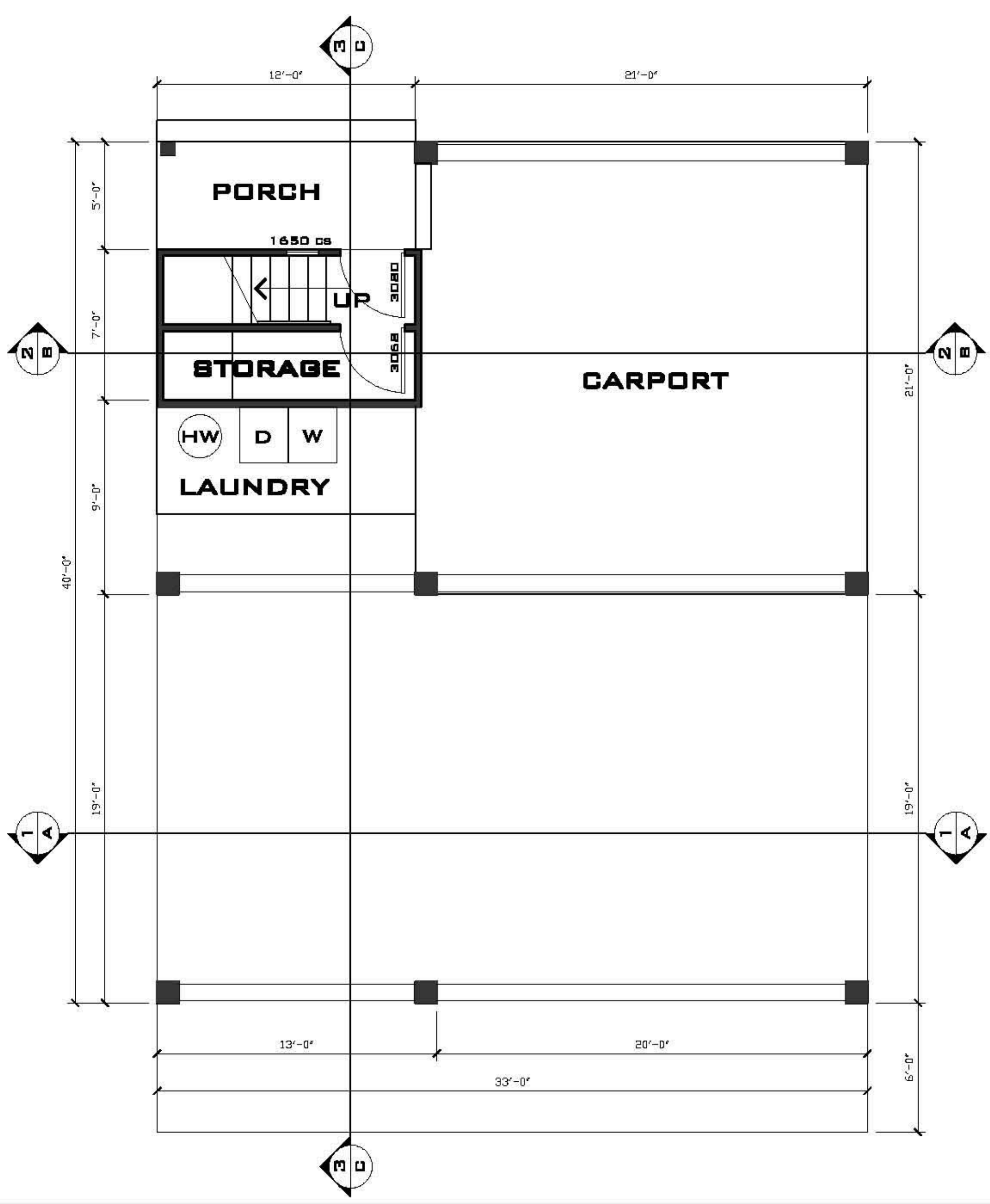
PLAN TYPE 1

SCALE: 1/8" = 1'-0"

PLAN TYPE 1

| | | |
|---|---|---|
| 92 | SF LIVING DOWNSTAIRS |
| 1186 | SF LIVING UPSTAIRS |
| 1278 | SF LIVING TOTAL |
| 441 | SF CARPORT |
| 258 | SF PORCH/LANAI |
| 1977 | SF TOTAL |

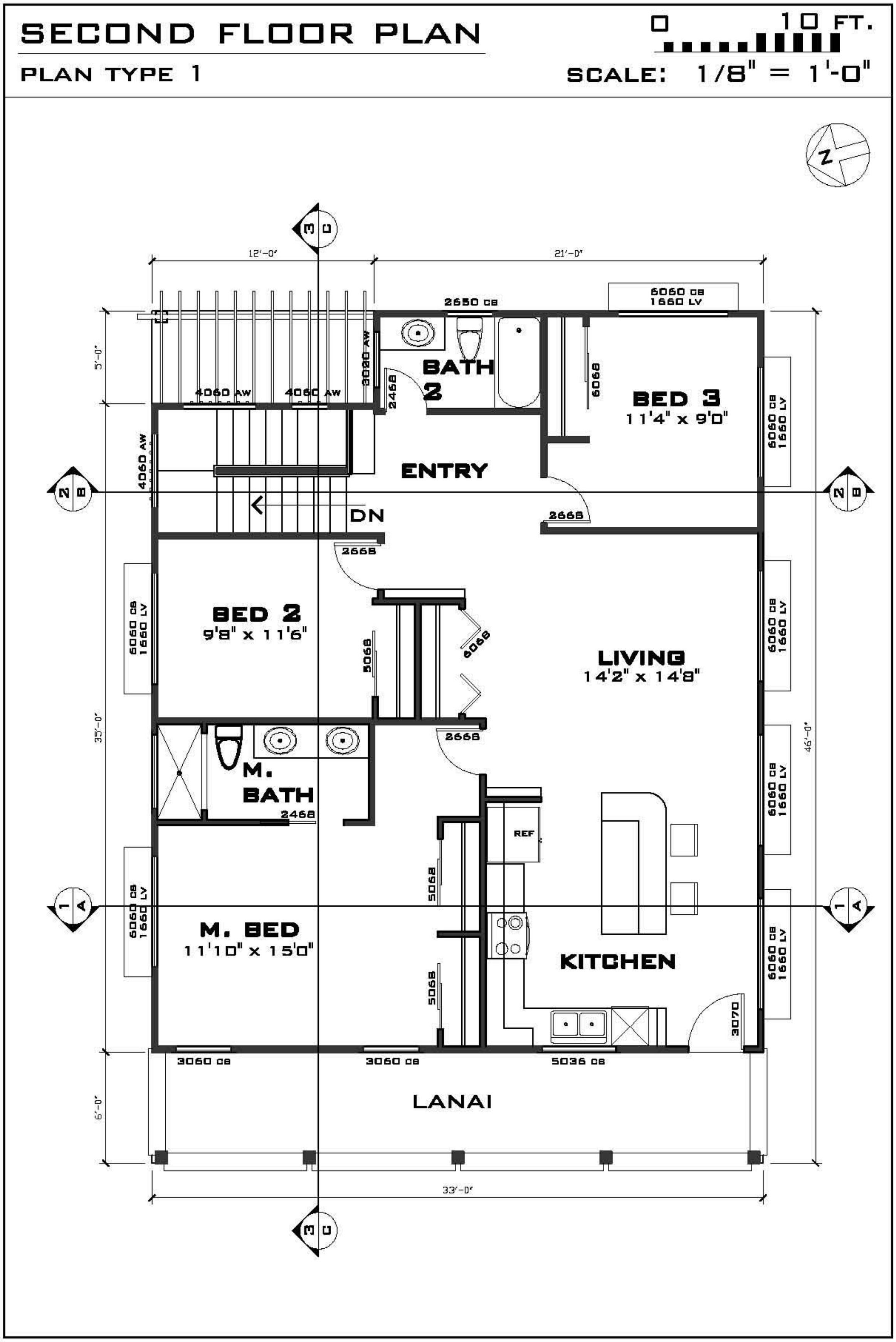
33' X 40' FOOTPRINT



# SECOND FLOOR PLAN

PLAN TYPE 1

SCALE: 1/8" = 1'-0"

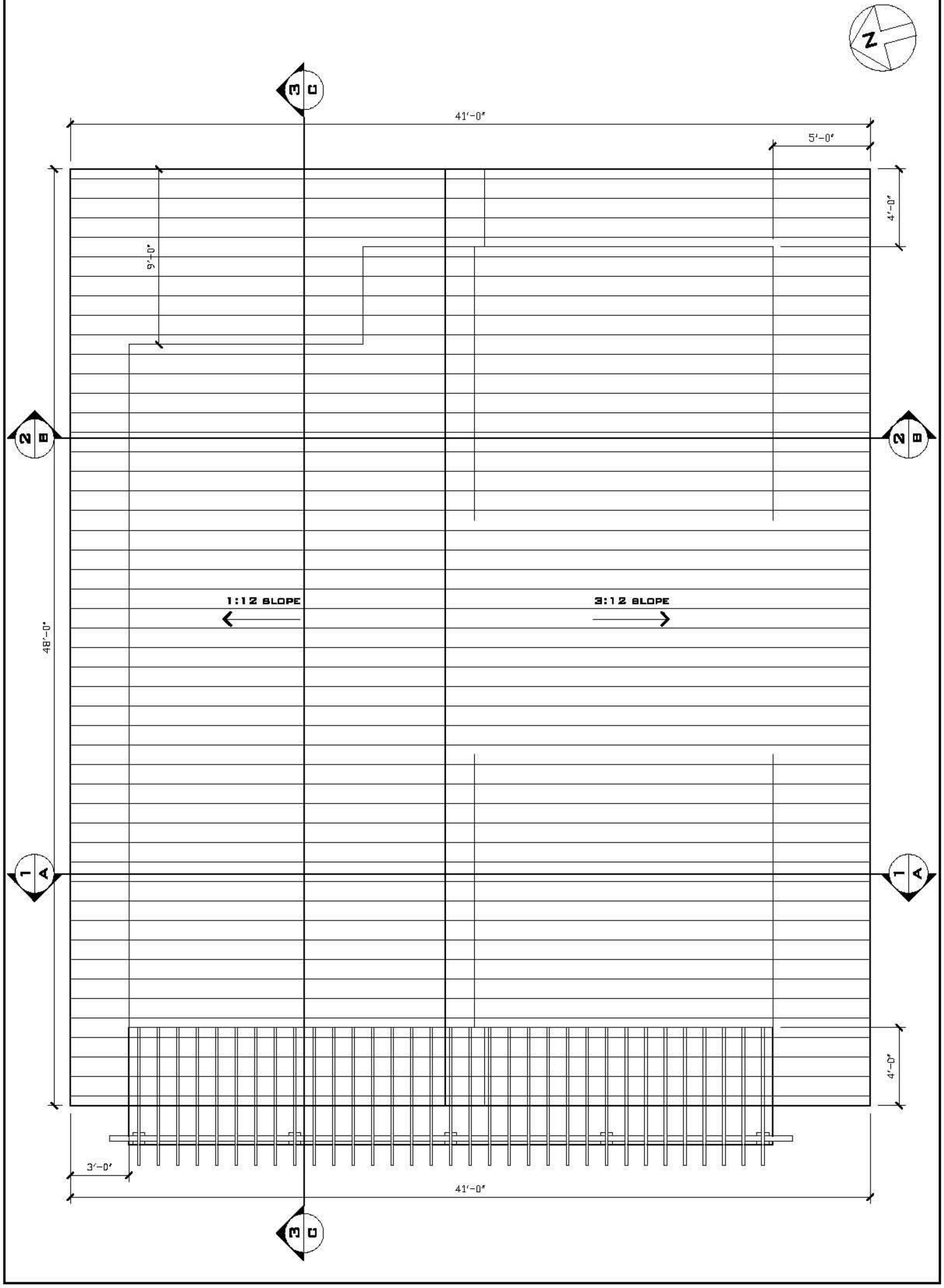


# ROOF PLAN

PLAN TYPE 1

0 10 FT.

SCALE: 1/8" = 1'-0"

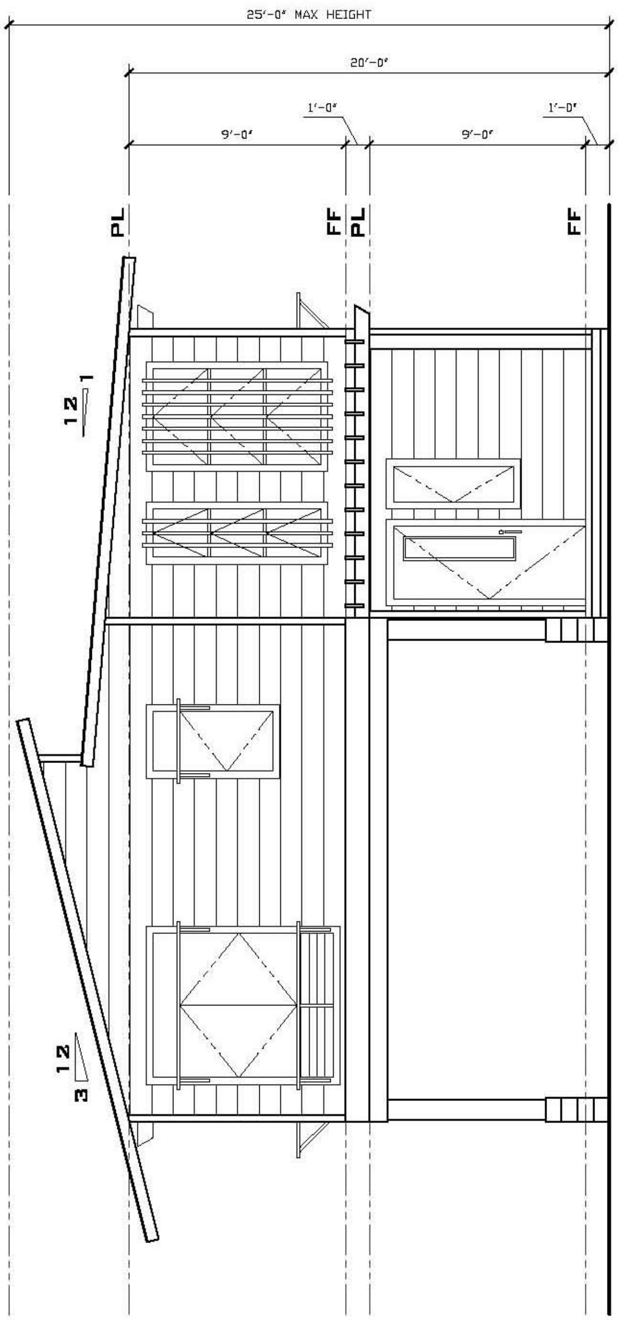


# FRONT ELEVATION

## PLAN TYPE 1

0 10 FT.

SCALE: 1/8" = 1'-0"

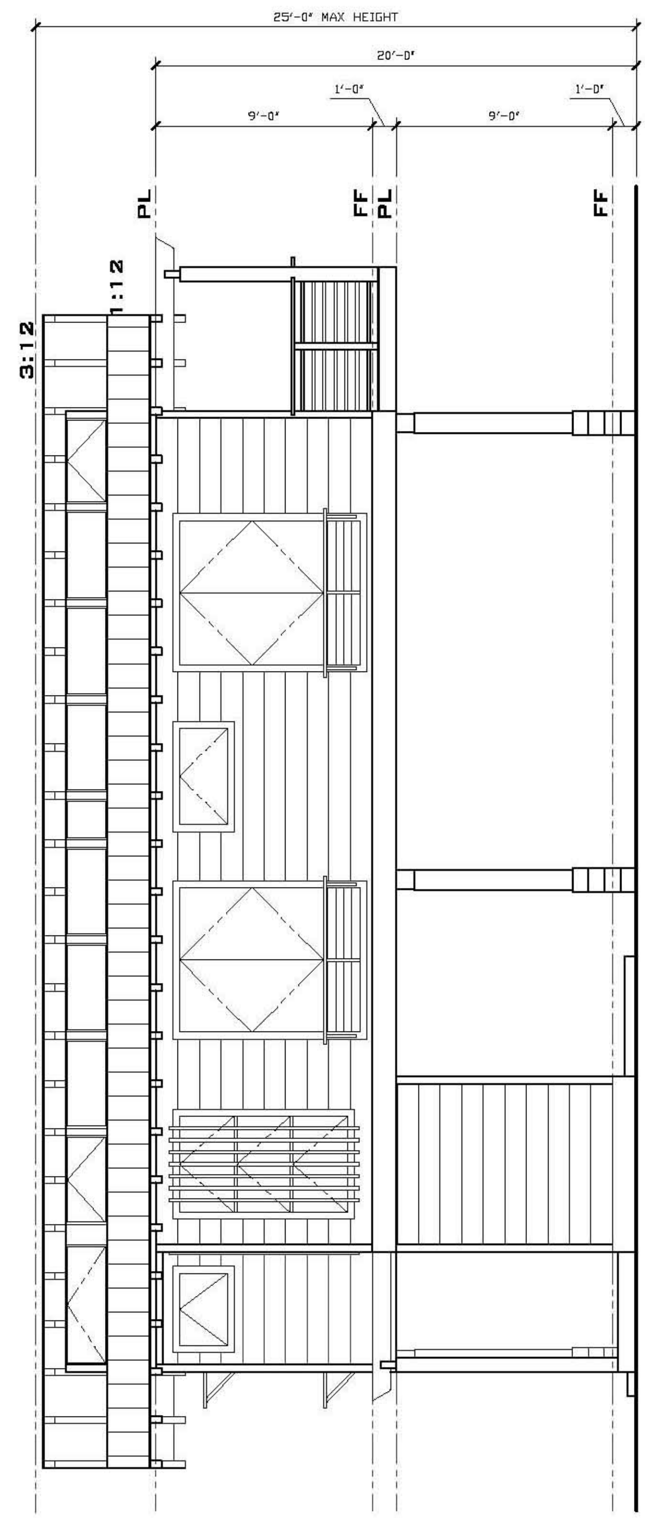


# RIGHT ELEVATION

## PLAN TYPE 1

0 10 FT.

SCALE: 1/8" = 1'-0"

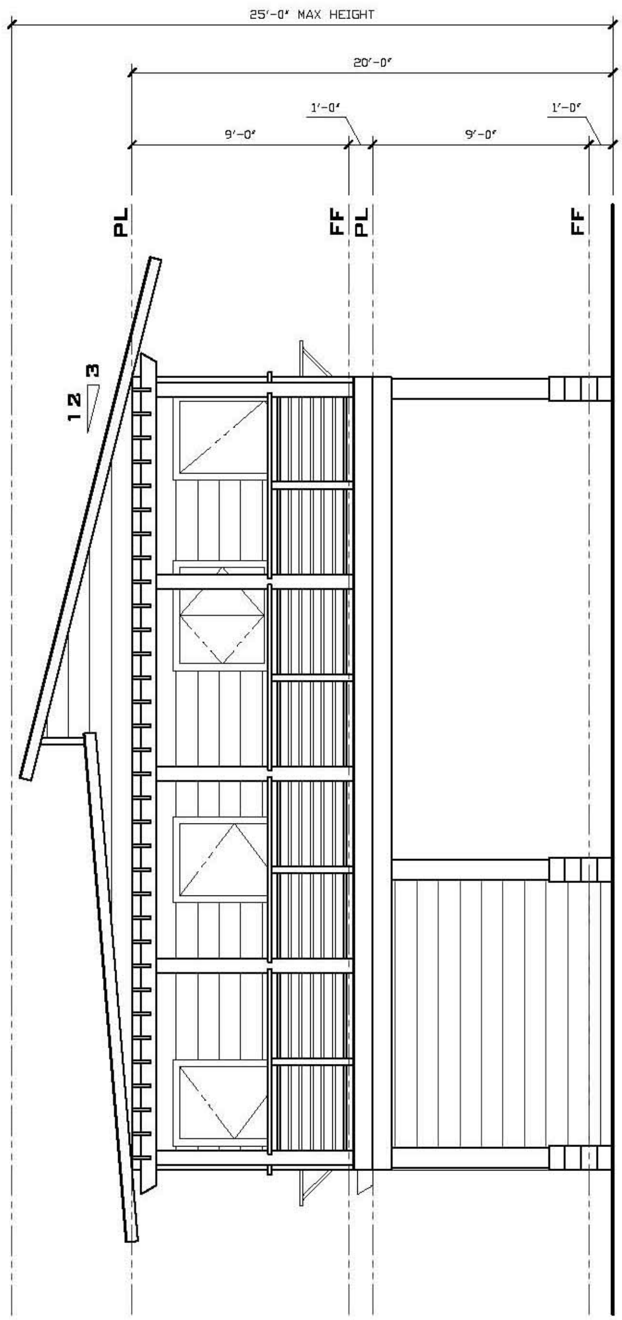


# REAR ELEVATION

## PLAN TYPE 1

0 10 FT.

SCALE: 1/8" = 1'-0"

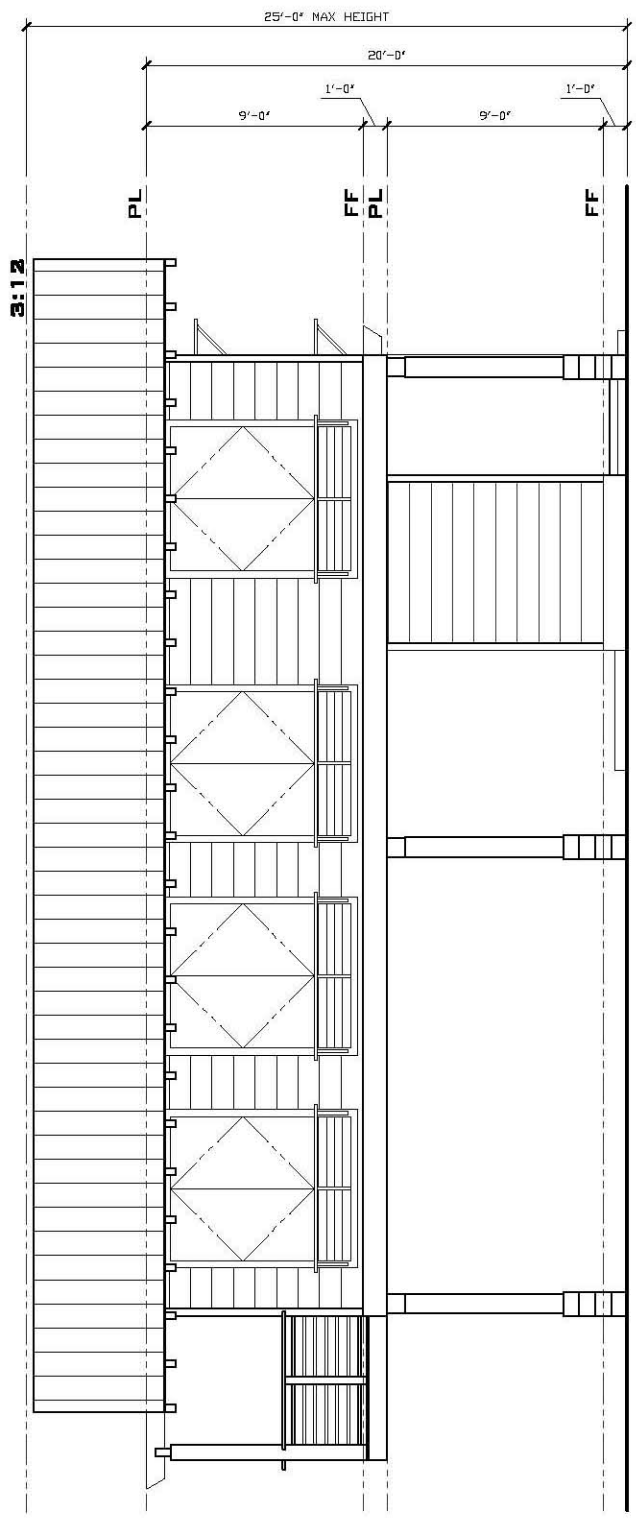


# LEFT ELEVATION

## PLAN TYPE 1

0 10 FT.

SCALE: 1/8" = 1'-0"

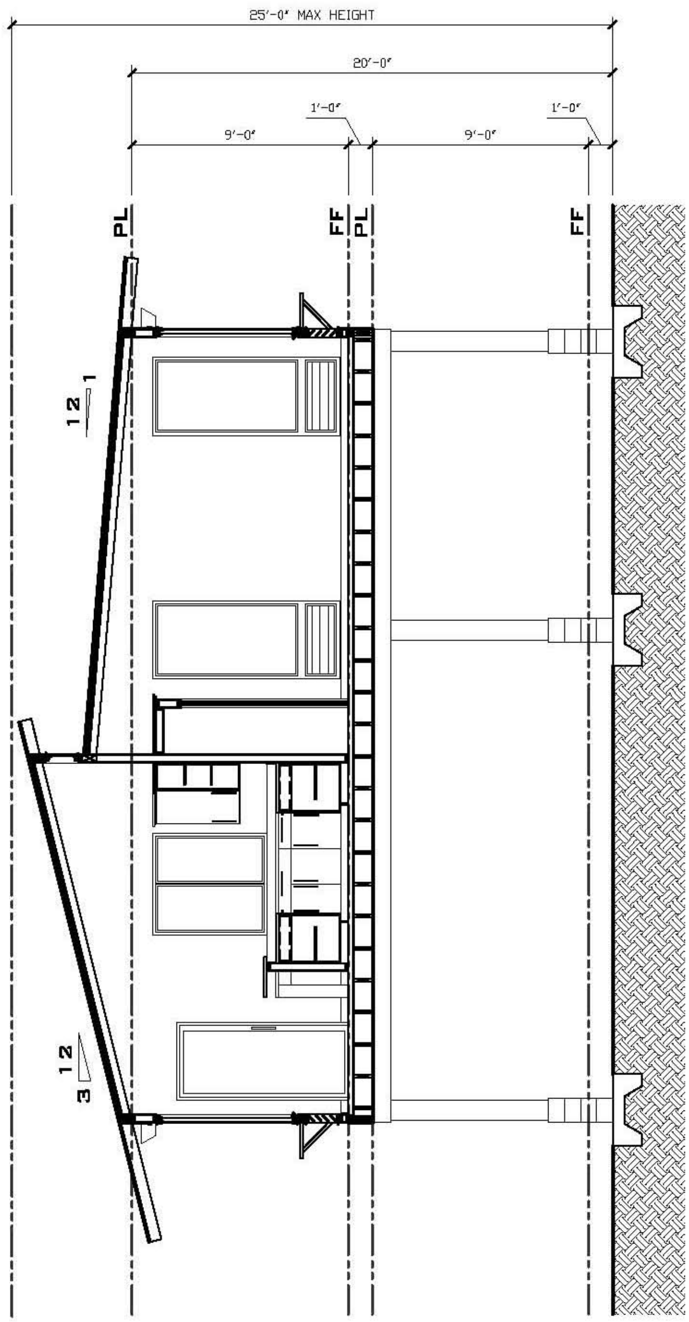


# SECTION A1

## PLAN TYPE 1

0 10 FT.

SCALE: 1/8" = 1'-0"



# SECTION B2

## PLAN TYPE 1

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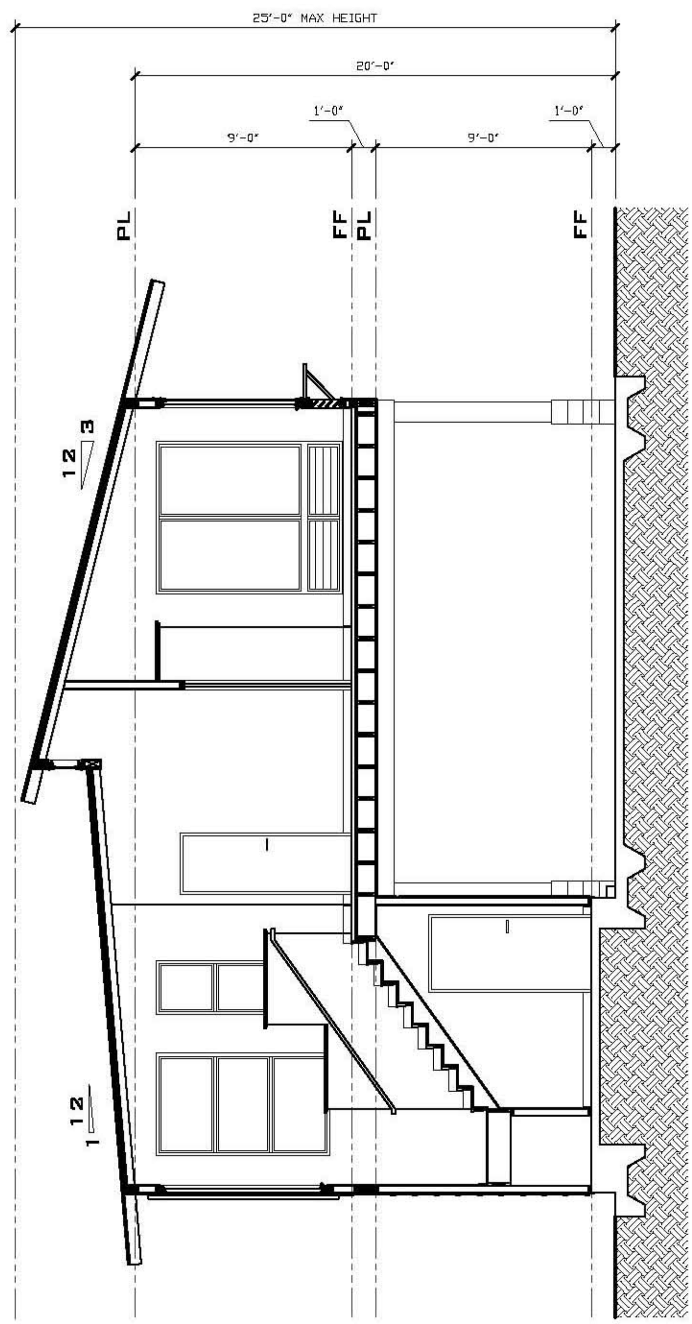

# SECTION C3

## PLAN TYPE 1

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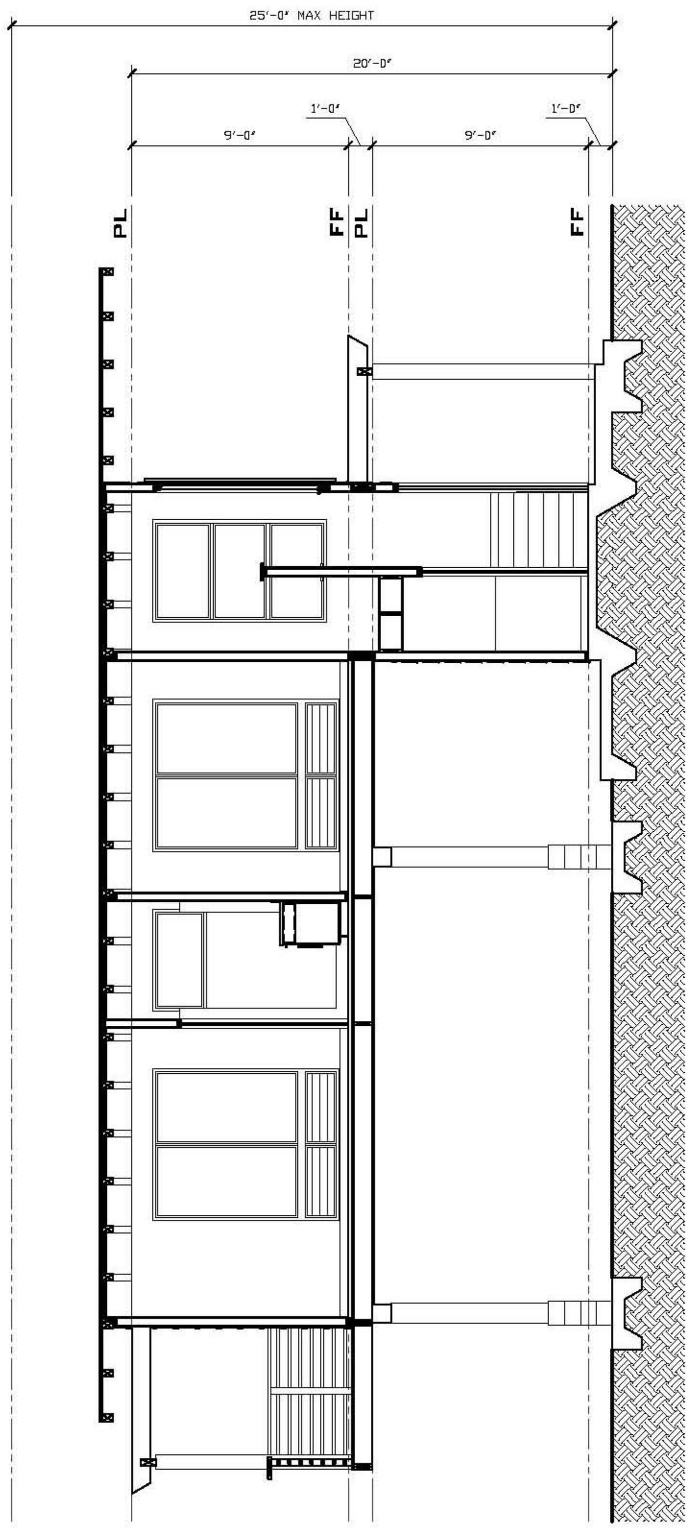
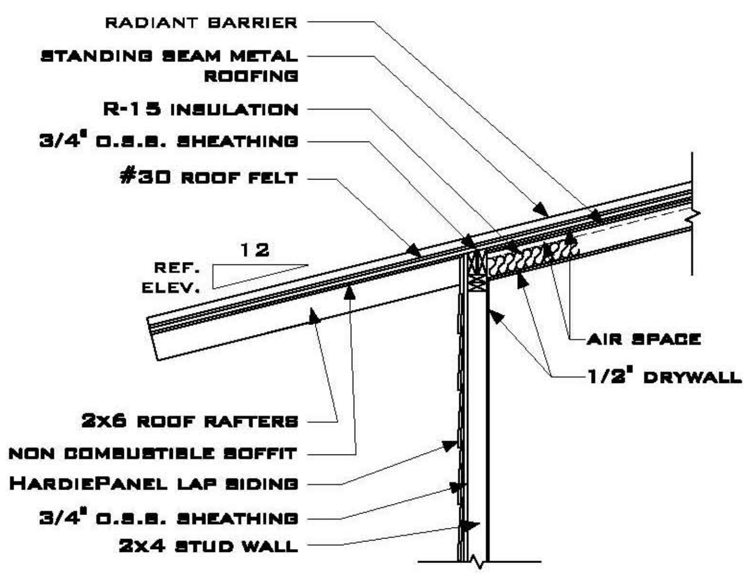
SCALE: 1/8" = 1'-0"



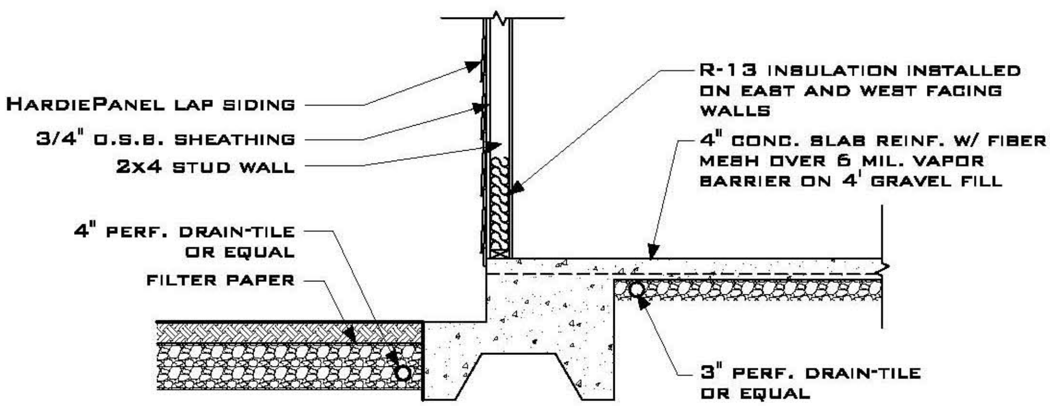
# DETAILS

## PLAN TYPES 1 AND 2

SCALE: NTS




TYPICAL EAVE DETAIL NTS




TYPICAL WALL DETAIL AT FOUNDATION NTS

# LIGHTING & POWER PLAN

## LEGEND TO DRAWINGS

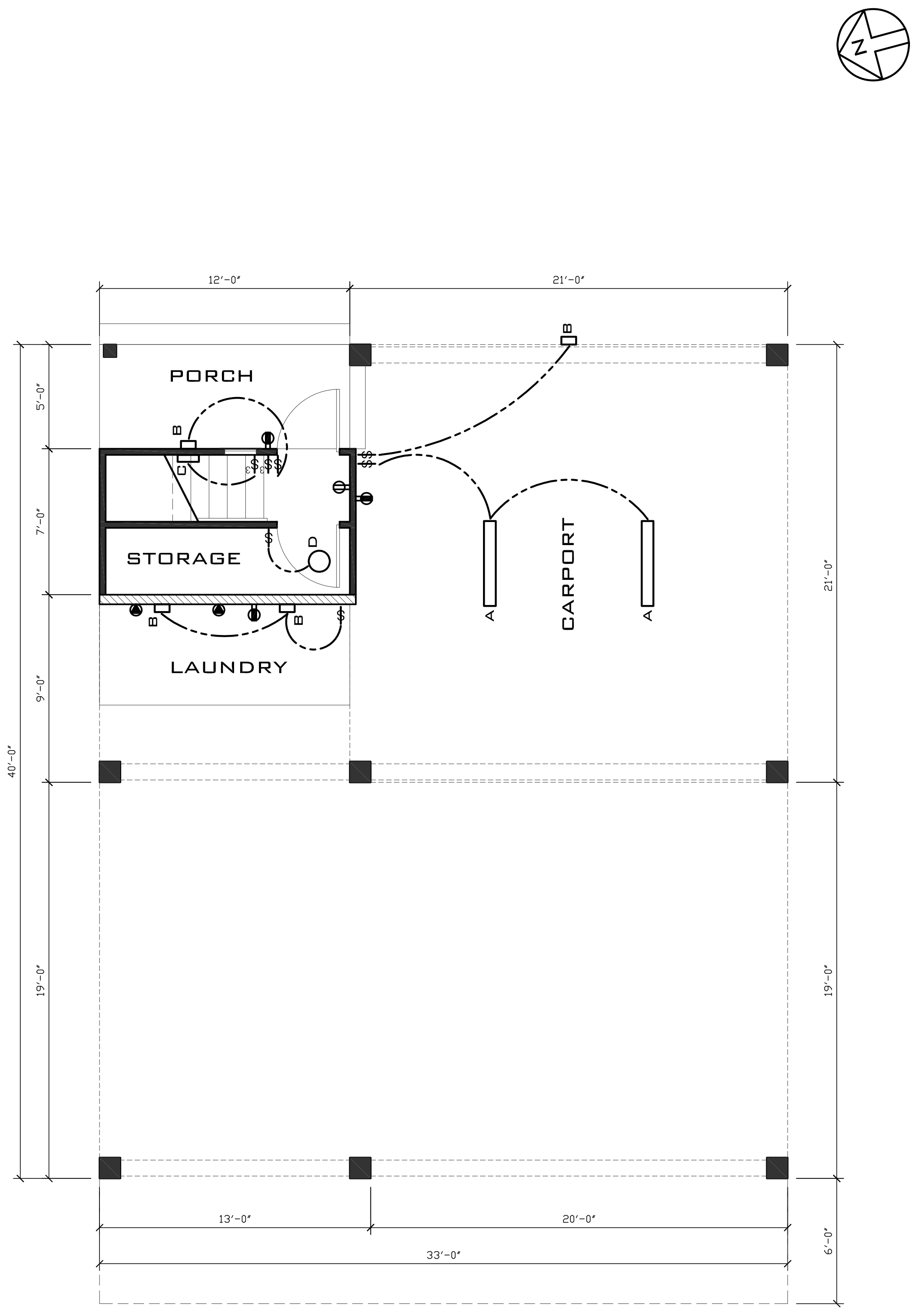
| | |
|---|---|
| A | AMERICAN FLUORESCENT SW SERIES: LINEAR |
| B | AMERICAN FLUORESCENT TRILIUM OUTDOOR SCONCE |
| C | AMERICAN FLUORESCENT RESTORATION SERIES: SCONCE |
| D | AMERICAN FLUORESCENT RESTORATION SERIES: FLUSH |
| E | AMERICAN FLUORESCENT SHERIDAN SERIES: VANITY 2 LAMP |
| F | AMERICAN FLUORESCENT SHERIDAN SERIES: VANITY 3 LAMP |
| G | AMERICAN FLUORESCENT RESTORATION SERIES: PENDANT 3 LAMP LINEAR |
| H | AMERICAN FLUORESCENT RESTORATION SERIES: PENDANT SINGLE LAMP |
| J | AMERICAN FLUORESCENT RESTORATION SERIES: PENDANT 3 LAMP ROUND |
| K | AMERICAN FLUORESCENT ECO-LED SERIES: UNDER CABINET |
| L | HUNTER PALERMO CEILING FAN WITH LAMP |
| M | HUNTER ULTRA QUIET BATHROOM FAN |
| S | SINGLE WALL SWITCH |
| $S^3$ | 3 WAY WALL SWITCH |
| | DUPLEX WALL RECEPTACLE |
| | GFCI WALL RECEPTACLE |
| | 240V WALL RECEPTACLE |

# LIGHTING & POWER PLAN

GROUND FLOOR

0 10 FT.

SCALE: 1/8" = 1'-0"

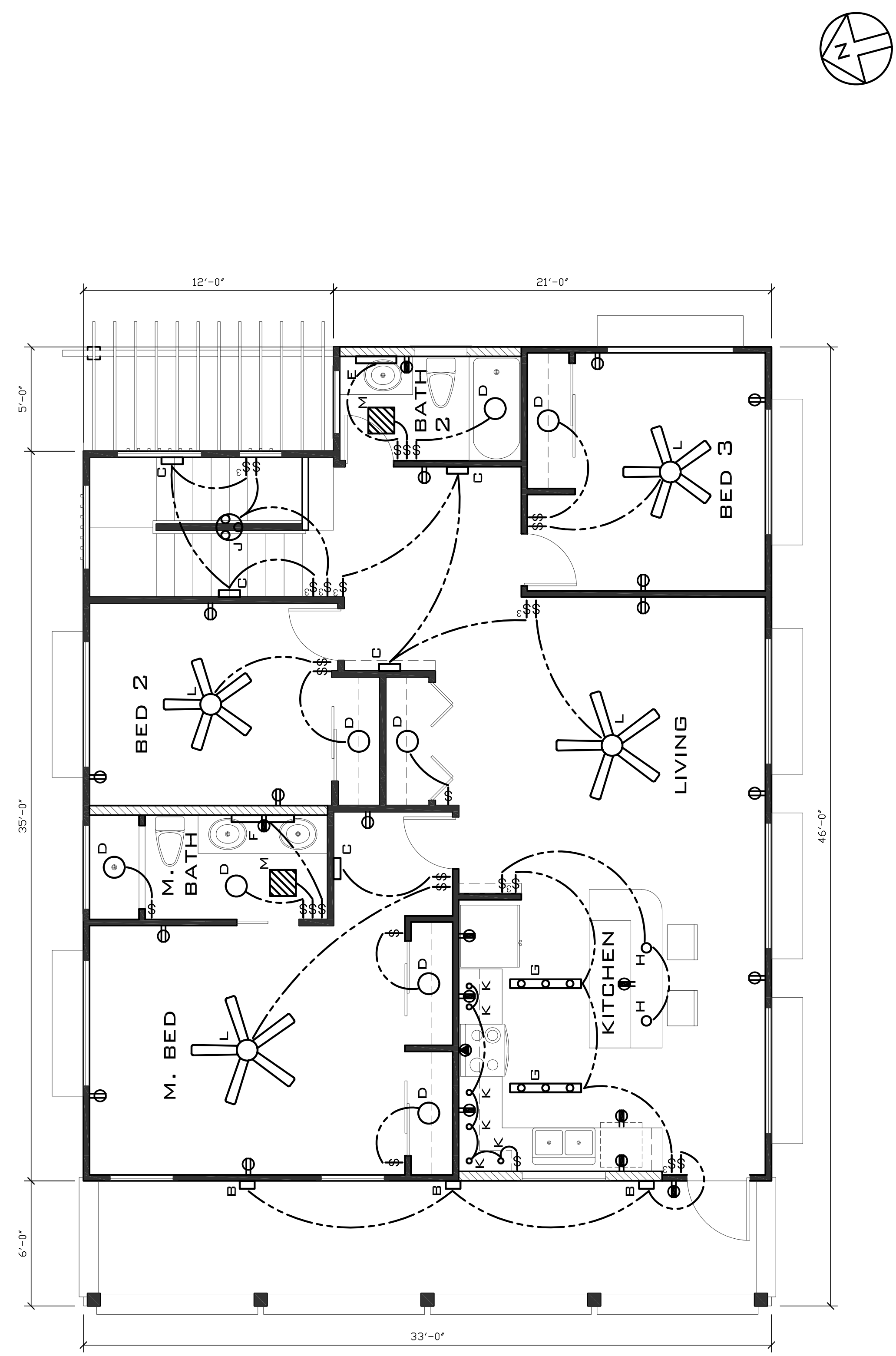


# LIGHTING & POWER PLAN

SECOND FLOOR

0 10 FT.

SCALE: 1/8" = 1'-0"



# GROUND FLOOR PLAN

PLAN TYPE 2

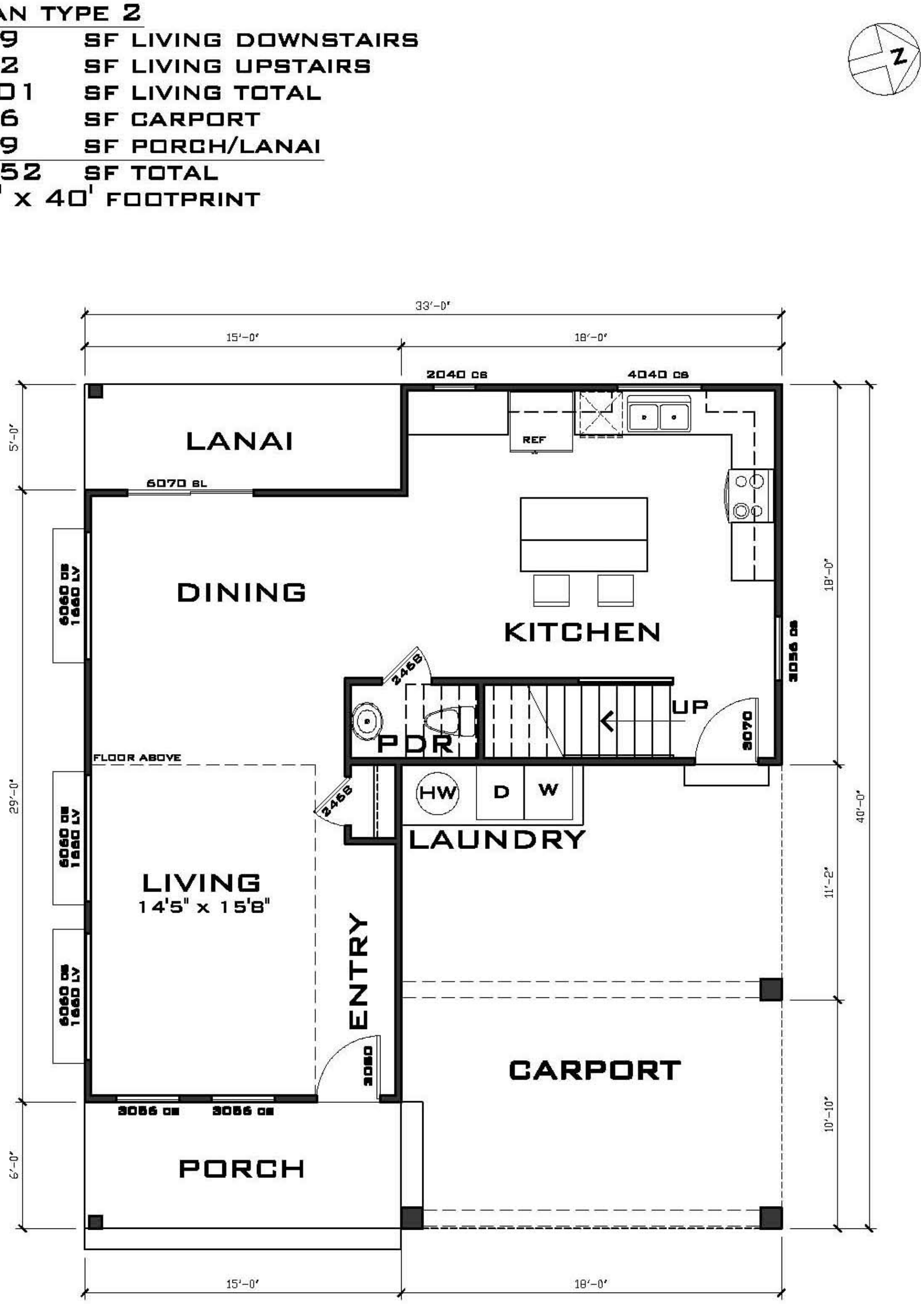
0 10 FT.

SCALE: 1/8" = 1'-0"

PLAN TYPE 2

| | |
|---|---|
| 759 | SF LIVING DOWNSTAIRS |
| 742 | SF LIVING UPSTAIRS |
| 1501 | SF LIVING TOTAL |
| 396 | SF CARPORT |
| 359 | SF PORCH/LANAI |
| 2252 | SF TOTAL |

33' x 40' FOOTPRINT

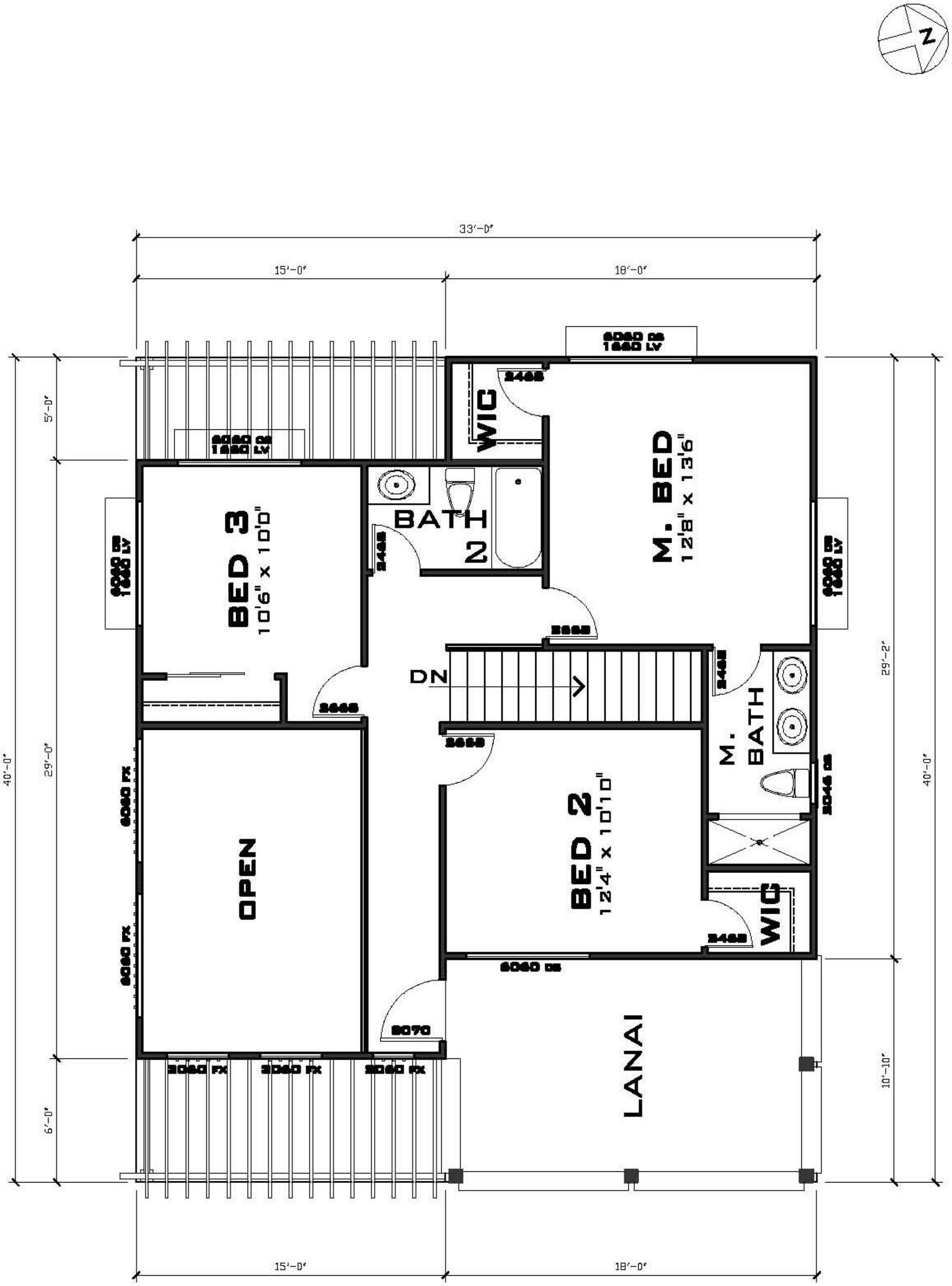


# SECOND FLOOR PLAN

PLAN TYPE 2

0 10 FT.

SCALE: 1/8" = 1'-0"

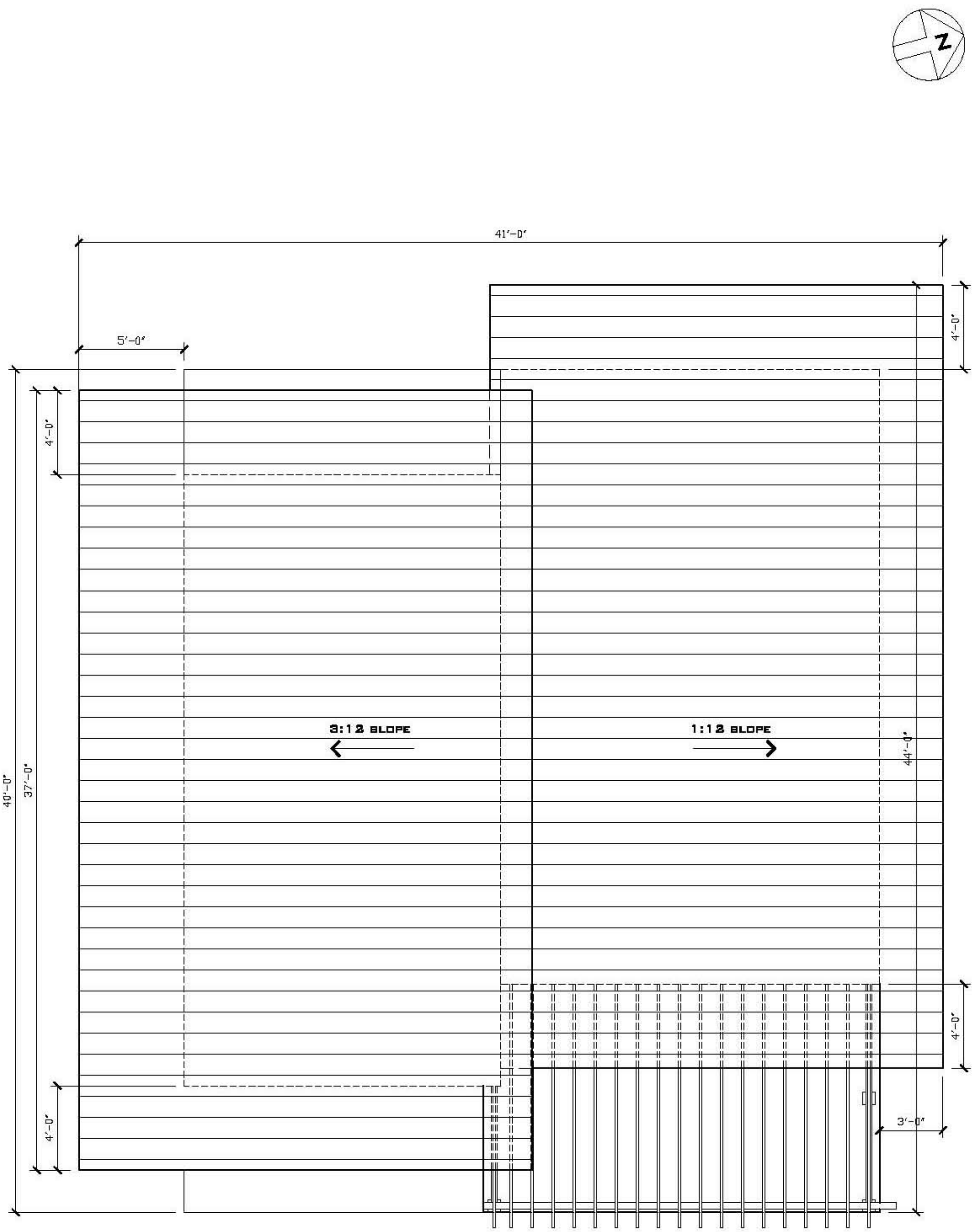


# ROOF PLAN

PLAN TYPE 2

0 10 FT.

SCALE: 1/8" = 1'-0"

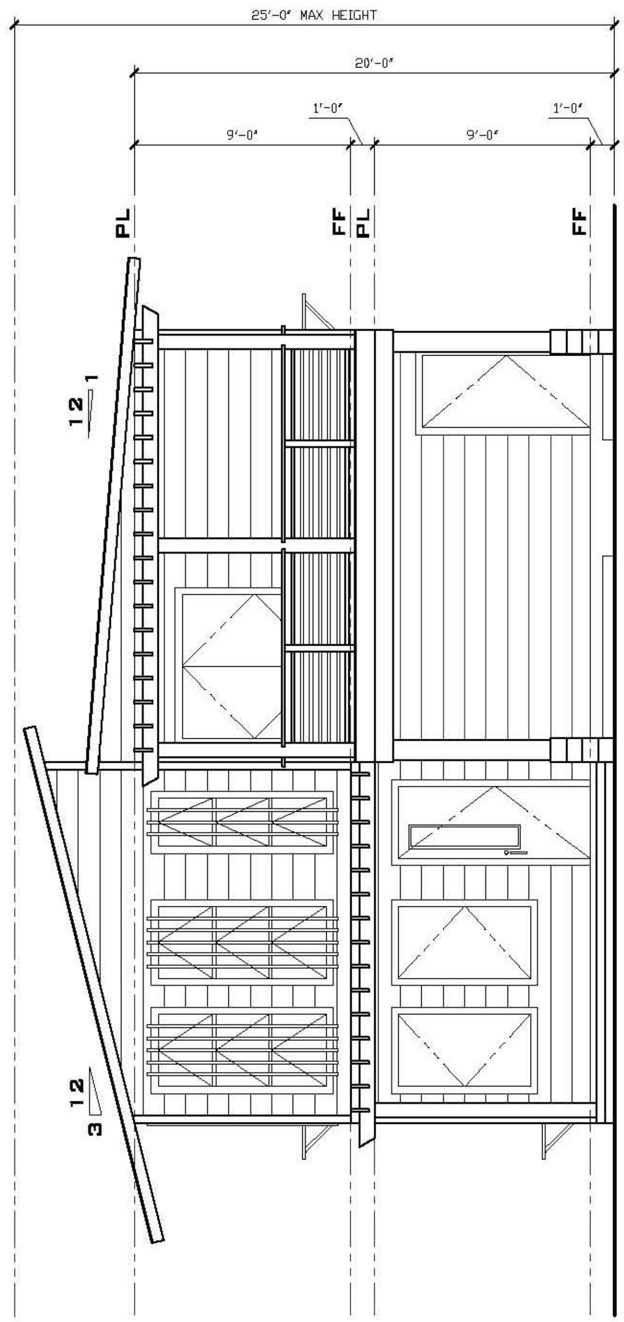


# FRONT ELEVATION

PLAN TYPE 2

0 10 FT.

SCALE: 1/8" = 1'-0"

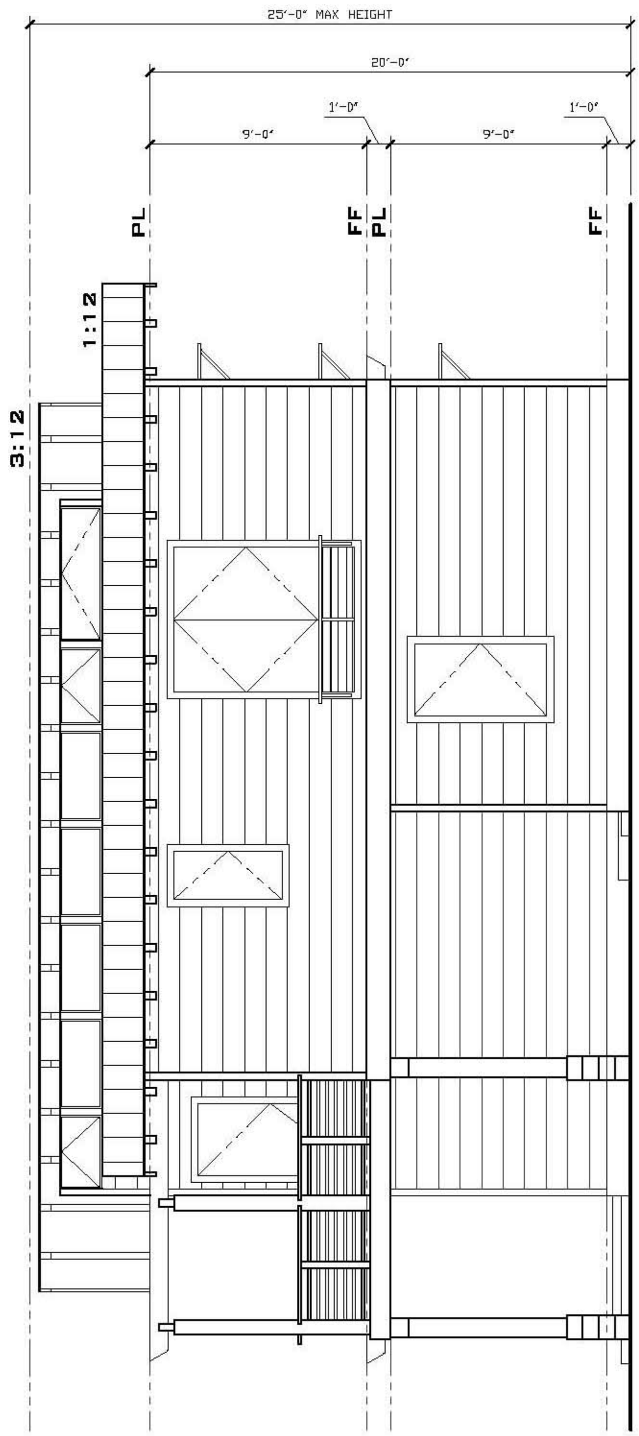


# RIGHT ELEVATION

## PLAN TYPE 2

0 10 FT.

SCALE: 1/8" = 1'-0"

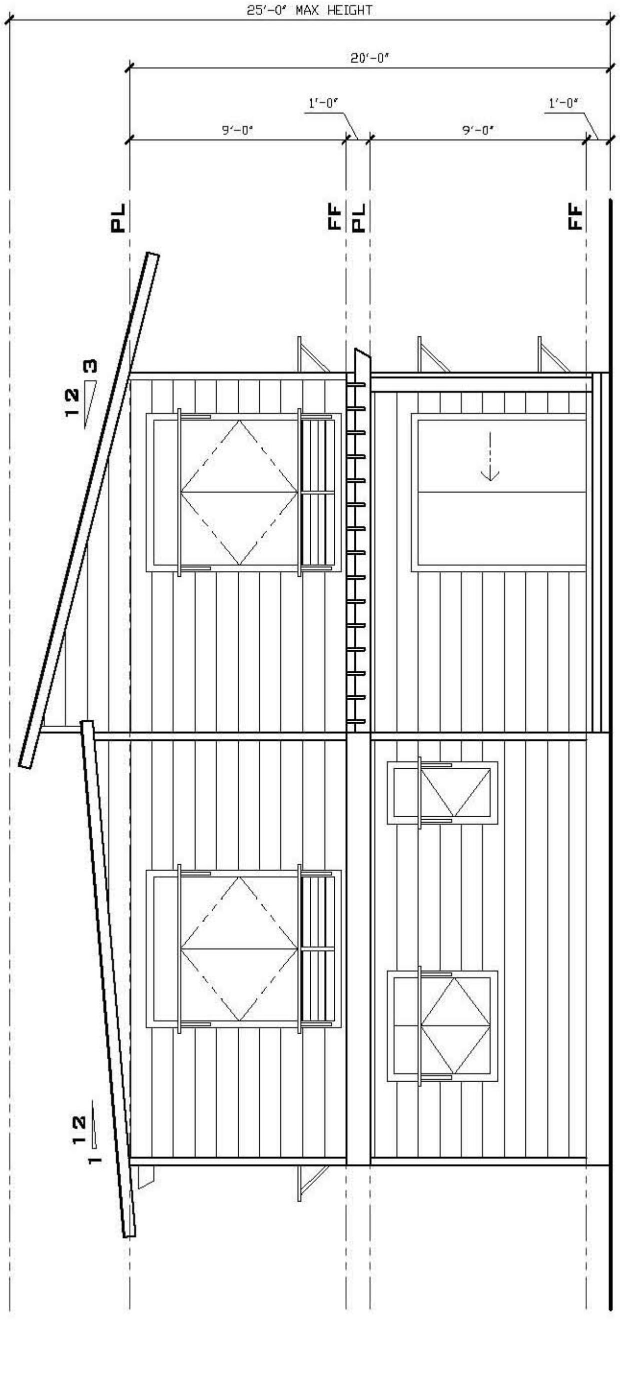


# REAR ELEVATION

## PLAN TYPE 2

0 10 FT.

SCALE: 1/8" = 1'-0"

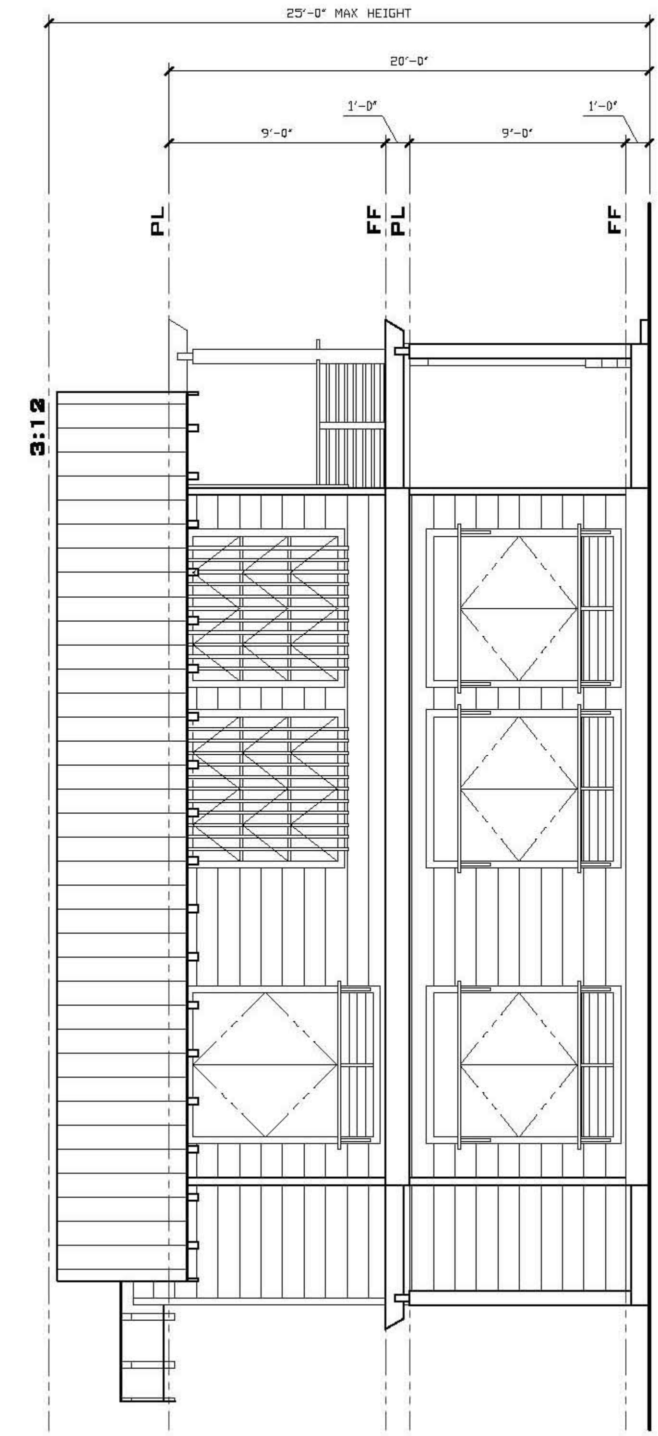


# LEFT ELEVATION

## PLAN TYPE 2

0 10 FT.

SCALE: 1/8" = 1'-0"



# *CHAPTER 7* *CONCLUSIONS*

This project set out to create a new standard of residential design and healthy living for Hawai‘i. The topics of climate conditions in Hawai‘i, passive cooling, thermal comfort and energy efficiency have been researched for the history and design strategies and techniques to create optimal residential designs for the Hawaiian climate. The research portion of this project has shown where sustainable design started, where it is now and why it is important to continue designing this way for the future. It is our responsibility to make smart, earth-friendly design decisions.

This project has covered the topics of sustainable “green” design, specifically passive cooling techniques, natural thermal comfort and energy efficiency strategies for Hawai‘i. The Green Homes at Lualualei has met the design goals of building affordable homes for the residents of Waianae, setting an example of green development and living in order to inspire future developments and providing a healthy living environment. The goal is that architects, designers and developers will use this project to continue developing climate appropriate architecture in Hawai‘i.

Three models were designed and analyzed using the computer programs Ecotect, WinAir and Radiance. Analysis was conducted on first a base case house model, then the first green house model and lastly the final green house model. The base case house model was designed as a typical house built in Hawaii that meets minimum code requirements. The first green house model has increased window area and roof overhangs, high-performance windows on the east and west facing walls, and uses metal roofing instead of asphalt roofing. The final green house model is further improved with insulation in the roof and east and west facing walls, higher-performance glazing used for all windows and includes trellises over the porch and lanai. Through the analysis in Ecotect, the final green house has shown improvements over both the base case house and the first green house model in each of the topics of interior thermal comfort, daylighting and energy efficiency.

Through analysis conducted in Ecotect, the final green house proves that it is more thermally comfortable and is more thermally neutral than the base case house. The final green home receives 13% less direct solar gains than the base case house during the peak monthly averages, which directly results in lowered interior temperatures. The interior temperatures in the final green house are not always within the natural comfort band for Hawai‘i, but have a higher percentage within the comfort band throughout the year than the base case house. The kitchen-living area in the final green house has temperatures within the comfort band 78.5% of the year, as compared to 70.4% in the base case house and 70.1% in the first green house. The bedrooms in the final green house are further improved with percentages as high as 88.1%.

Natural ventilation plays a crucial role in maintaining natural thermal comfort in the homes. The final green house is tested and analyzed compared to the base case house for the high and low monthly averages. Based on the low monthly average wind speed of 2.9 m/s the interior of the final green house receives wind speeds of up to 1.3 m/s, which is close to the goal of 1.5 m/s. The final green house receives interior wind speeds of up to 2.5 m/s when testing wind speeds for the high monthly average of 4.2 m/s. Throughout the year the final green home receives enough natural ventilation to greatly improve the perceived natural comfort for the occupants.

The final green house analysis has shown daylighting improvements over the base case house, while also neutralizing interior temperatures and improving thermal comfort. Each of the main spaces of the homes provides sufficient daylight to greatly reduce electric lighting needs during daylight hours. The master bedroom achieves a yearly daylight factor of 4.07% and bedroom two achieves 3.96%, both of these spaces exceed the minimum daylight factor requirements of 2% for daylit spaces. The kitchen-living area achieves a yearly daylight factor of 6.08% and bedroom three achieves 8.45%, both of these spaces exceed the minimum daylight factor requirements of 5% for well daylit spaces. Through the designs and analysis the overall daylight in the final green house is more evenly dispersed through the spaces, which reduces high contrast areas and glare and improves the overall luminance of the homes.

The energy efficiency and daylighting goals for this project were to design homes that are at least 30% more energy efficient than state energy code minimums and to provide at least 30% more natural light access than city code demands. Both of the plan types meet the goal for providing 30% more natural light access minimums. Plan one has a total of 43% window area to floor area, which is in increase of 33% over the minimum. Plan two has a total of 40% window area to floor area, which is an increase of 30% over the minimum.

By using ENERGY STAR rated appliances and fixtures, the homes show improved energy efficiency and reach the goal of being 30% more energy efficient than state energy code minimums. The refrigerator specified for this project uses 20% less electricity than national standards, the dishwasher specified uses 35% less electricity than national standards, and the clothes washer specified uses 46% less electricity than federal standards and 61% less water than the federal maximum. All of the lighting and ceiling fans used in the homes for this project are ENERGY STAR rated. The rating is based on the fixtures using less energy by requiring 120V ballasts and low wattage lamps. Using 13W CFW lamps instead of 60W incandescent bulbs will reduce energy usage by about 78%. Reducing energy usage in homes not only saves the homeowner money on electric bills, but also reduces the need and use of limited fossil fuels and reduces our carbon footprint.

With the depletion of fossil fuels and the high rising costs of electricity it is important to study and implement design strategies suggested here to provide a clean, healthy world for future generations. The hope is that architects, designers and developers take these strategies and techniques into serious consideration for the immediate and everlasting future of the built environment. This project shows how a residential home in Hawaiʻi can accomplish improved thermal comfort and energy efficiency through building design and using eco-friendly and energy efficient materials, appliances and fixtures.

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